

Sensorimotor Realities: Formalizing Ability-Mediating Design for Computer-Mediated Reality Environments

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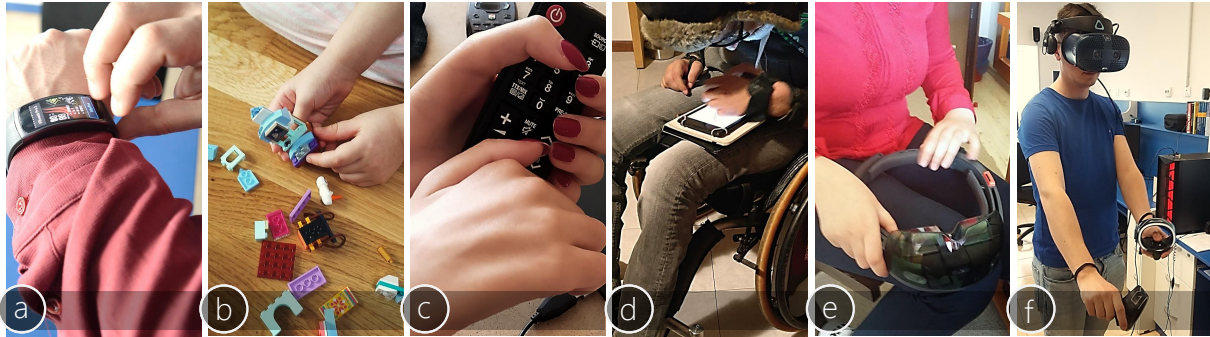


Figure 1: Various sensorimotor abilities enable a diversity of skills in everyday life: (a) a young adult's precise touch on a small wearable; (b) a six-year-old child assembles tiny Lego pieces; (c) a person with Spinal Cord Injury uses a TV remote control by firmly gripping it with two hands; (d) a wheelchair user employs a tablet device by supporting it on his thigh; (e) a blind person moves her hands across a HMD to understand the form factor of the device; and (f) a user immersed in VR manipulates virtual objects. Sensorimotor Realities, introduced in this work, are a new concept and framework to characterize and foster research contributions and interactive systems that mediate skills such as these, while capitalizing on the heterogeneity of human sensorimotor abilities.

ABSTRACT

We introduce “Sensorimotor Realities,” a new concept in the XR landscape and corresponding technology-agnostic framework for computer-mediated perception and motor action. Sensorimotor Realities capitalize on the heterogeneity of human sensorimotor abilities to support conceptualization, characterization, and design of computer technology that leverages existing abilities in new, computer-mediated worlds. We introduce a conceptual space for Sensorimotor Realities with six dimensions, discuss examples of interactive systems in this space, and show how Sensorimotor Realities are distinct in nature and goal from Augmented, Mixed, Virtual, and Mediated Reality. We capitalize on Sensorimotor Realities to propose “ability-mediating design,” an approach to designing accessible interactive computer systems that complements ability-based design. We discuss how Sensorimotor Realities offer new opportunities for research and development at the intersection of XR, wearable computing, ambient intelligence, and accessible computing, and draw a research roadmap with three major directions of scientific investigation.

Index Terms: H.5.1 [Multimedia Information Systems]: Artificial, augmented, and virtual realities; K.4.2 [Social Issues]: Assistive technologies for persons with disabilities

1 INTRODUCTION

Human sensorimotor abilities are diverse, vary between individuals and within the individual, and are affected by the context in which they are applied [4, 46]. They are determined by the human anatomy and biology, and influenced by our learning experiences, interactions with the world and others, but also by aging, illness, and injury. Moreover, fatigue [8], cognitive stress [12], inattentional

blindness [75], and situationally-induced impairments [71] temporarily affect our abilities to perceive the world and act effectively in it. Figure 1 shows a diversity of skills enabled by sensorimotor abilities in context, from interacting with the small display of a smartwatch (1a) to assembling tiny Lego pieces (1b) to coping strategies developed by people with motor impairments to make everyday objects more accessible (1c, 1d) and by people with sensory impairments to make the physical world more apprehensible (1e).

The same sensorimotor abilities that make humans effective in the physical world are also leveraged for interactions in new environments, such as computer-mediated [47], simulated [3], and augmented worlds [5, 52] (Figure 1f), that feature synthetic stimuli [34], illusory effects [70], and different laws of physics [11]. For instance, in Augmented and Mixed Reality (AR/MR), the interplay between physical and virtual objects facilitates learning in context [63]. In Mediated Reality (XYR) [47, 49], perception is extended beyond the biological limits of human sensing, enabling new phenomenological experiences in darkrooms [49]. In Imaginary Reality (IR) [7], perception is complemented by mental imagery, either partially [7, 92] or fully [67], making action effective despite the scarcity or absence of the stimuli needed for sensorimotor coupling. These emerging environments, worlds and, ultimately, realities afford new sensorimotor experiences, such as amplified perception [2, 39, 106] and enhanced motor skills [62, 73], but also perception that is diminished [65] and motricity that is reduced [55] on purpose. Users’ sensorimotor abilities are repurposed in a process of mediation to support new skills and interactive experiences.

It should follow thus that the design of computer-mediated worlds and interactive systems needs to capitalize primarily on users’ sensorimotor abilities with an approach that is not just user-centered [27, 56], but focused on the users’ specific abilities as advocated by ability-based design [102]. However, unlike the scope of ability-based design, the act of mediation, as the distinctive feature of computer-mediated reality [47, 48], repurposes users’ abilities to enable new skills and experiences. For example, with Chrome-

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Glasses [39], the ability of people with Protanopia to distinguish certain colors from the visible light spectrum is repurposed to enable the skill of distinguishing between red and green. With HandMorph [55], the finger dexterity ability of a toy designer is repurposed to enable the experience of the smaller grasping range of a child playing with the toy. In these examples, *computer mediation that repurposes abilities, instead of computer systems designed to match and adapt to abilities [102, 103], is key to the new experience.*

Computer-mediated reality creates an entirely new scope for designing accessible interactive systems compared to ability-based design and enables distinct opportunities for innovation. Unfortunately, there is a lack of concepts and terminology for researchers and practitioners to capitalize on for the *design of interactive systems that center on users' abilities as these abilities undergo mediation.* In this context, the contributions of our work are as follows:

1. We introduce “Sensorimotor Realities (SRs),”¹ a new conceptual framework depicting a new type of reality with distinctive characteristics in the XR landscape² and enabled by the integration of smart wearables and smart environments. We show how SRs relate to other reality concepts, such as AR [5], MR [52], and XYR [47], yet stand out distinct in this landscape.
2. We propose a six-dimensional conceptual space for SRs to characterize and compare interactive systems addressing mediation of sensorimotor abilities in computer-mediated worlds.
3. We use SRs to introduce “ability-mediating design,” a complementary approach to ability-based design [102, 103], for which we outline three design principles: (1) mediation of perception and action, (2) world coverage, and (3) instrumentation of the body and the environment. To exemplify ability-mediating design and demonstrate the use of the SRs conceptual space, we document the design process of an accessible HoloLens application implementing Augmented Reality Television for a user with phocomelia that presents specific sensorimotor abilities. We also use our example to differentiate between the distinguishing qualities and characteristics of ability-based and ability-mediating design and to show their complementarity.
4. To foster further exploration of ability-mediating design, we propose a research roadmap for SRs and present the vision of computer-mediated worlds where users' sensorimotor abilities are mediated to support a diversity of readily accessible skills and corresponding interactive experiences in those worlds.

2 RELATED WORK

We relate to various forms of computer-supported realities in order to contextualize SRs in the XR landscape. We also relate to ability-based design [102, 103], in relation to which we propose our complementary ability-mediating design approach, and to Fleishman's [24] and Gentile's [25] frameworks for human abilities and skills, on which we capitalize to formalize ability-mediating design.

2.1 Computer-Supported Realities

SRs relate to other types of computer-supported realities, including Augmented, Mixed, Virtual, Mediated, and Multimediated reality [5, 49, 52, 59, 98]. We adopt the formalization employed by Mann *et al.* [49] to discuss these concepts as supersets and subsets, respectively. For example, AR is a subset of MR according to Milgram and Kishino's [52] Reality-Virtuality continuum. Building on this continuum, Skarbez *et al.* [76] redefined MR as the environment in

¹Note our use of the plural, including in the acronym (SRs), to acknowledge the heterogeneity of human sensorimotor abilities and the fact that each of us experience everyday a range of such realities as our abilities are influenced by many factors.

²eXtended Reality (XR) as the encompassing concept and technology for AR, MR, and VR and, by extension in this work, XYR and IR.

which real and virtual world stimuli are presented as a single percept. According to Mann *et al.* [47], MR is a subset of XYR.³

In this landscape, SRs have a larger scope than XYR [47, 49], since they integrate motor action explicitly, whereas XYR is focused on perception and was originally introduced to address aspects of visual perception and attention, i.e., XYR “allows us to filter out things we do not wish to have thrust upon us against our will ... [and] to implement a ‘visual filter’” to “modify our visual perception of visual reality” (p. 3). Later [48], the application range of XYR was extended to other senses: “although the visual modality is most often used in mediated reality systems based on current technology, other modalities such as touch, taste, and olfaction may be mediated as well” (p. 205). Tang [80] used XYR as a framework to inform designs and evaluations of bearable prostheses that incorporated both sensors (e.g., sonic range finders attached to the neck) and actuators (e.g., muscle stimulation arm bands) to explore the effect of such devices on user perception and autonomy. By adding actuators to XYR, new dimensions open towards Multimediated Reality, a recent proposal by Mann *et al.* [49] to describe “All Reality” (*R or ZR) as “a multidimensional multisensory mediated reality that includes not just interactive multimedia-based ‘reality’ for our five senses, but also includes additional senses (like sensory sonar, sensory radar, etc.) as well as our human actions/actuators” (p. 1). Sensorimotor abilities fit within this perspective that considers both perception and motor action. However, both XYR and *R are agnostic to differences in human abilities, on which SRs capitalize and, thus, XYR and *R do not offer the tools to characterize changes in those abilities.

2.2 Ability-Based Design

Ability-based design [102, 103] promotes interfaces that are general, yet flexible to address a range of users, but also interfaces that are personalized to specific user groups or individual users. Seven principles guide practitioners of ability-based design: *ability*, *accountability*, *availability*, *adaptability*, *transparency*, use of *context*, and *performance*. For example, *ability* means that designers focus on users' abilities instead of disabilities, *availability* means that technology should be affordable and available and, according to *adaptability*, interfaces provide the best possible match to users' abilities. Ability-based design promotes interactive systems that match and adapt to users' specific abilities instead of users developing coping strategies to overcome accessibility challenges [31, 53, 87]. However, *computer-mediated reality creates a new scope for accessible interactive systems compared to that of ability-based design since it enables design of systems that center on abilities undergoing a process of mediation.* To address the latter, we introduce ability-mediating design in Section 3 and illustrate the complementarity between ability-based and ability-mediating design with an example. Next, we focus on two frameworks for human abilities and skills.

2.3 Two Frameworks for Human Abilities and Skills

Fleishman [23] distinguished between the concepts of *ability* and *skill* in his approach to understanding human performance. Abilities refer to general traits as “organismic factors that the individual brings with him when he begins to learn a new task” (p. 1018), while skills refer to the level of task proficiency. Fleishman's objective was to describe skills in terms of general ability requirements to account for human performance on a wide range of tasks with a relatively small number of abilities. This approach has been key to motor learning, motor control, and individual differences psychology (see [46]) that have adopted Fleishman's definition of ability as the trait determinant of the achievement potential of specific skills. The current definition of motor skills specifies “voluntary control over movements of the joints and body segments to achieve a goal” [46]

³The acronym XYR [49] for Mediated Reality describes two axis: X is the Reality-Virtuality continuum of Milgram and Kishino [52] and Y is the new mediality axis introduced by Mann [47].

(p. 3), where the words “goal,” “voluntary,” and “movement” are key. Various abilities, relatively independent according to the specificity hypothesis [29, 46], underlie the performance of skills.

The identification of abilities is thus key to understanding skills and human performance. To this end, Fleishman’s [23, 24] taxonomy of eleven perceptual-motor abilities has been influential in motor learning and control; see Anderson *et al.*’s [4] survey on individual differences in motor learning and Magill and Anderson’s [46] discussion of motor skill classification systems. Since perceptual-motor ability categories are directly relevant to our scope,⁴ we briefly summarize them here: (1) *multilimb coordination* is the ability to coordinate the movements of a number of limbs, (2) *control precision* is precise adjustment of the large muscle groups, (3) *response orientation* is the ability to rapidly select a motor response following a stimuli, (4) *reaction time* is the ability to respond fast to a stimuli, (5) *speed of arm movement* represents the ability to make a gross, non accurate movement, (6) *rate control* is used for timing continuous responses to changing stimuli, (7) *manual dexterity* for skillful arm-hand movements to manipulate large objects, (8) *finger dexterity* for skillful manipulations of tiny objects, (9) *arm-hand steadiness* is the ability of arm-hand positioning while minimizing strength and speed, and (10) *wrist, finger speed* and (11) *aiming* are tapping abilities. Note that this list is not exhaustive, but comprises “the fewest independent ability categories which might be most useful and meaningful in describing performance in the widest variety of tasks” [24] (p. 352). Given the large adoption [4, 46] of Fleishman’s taxonomy, we use its categories to guide practical SRs applications.

Magill and Anderson [46] discussed several skill classification systems, and concluded that Gentile’s [25] taxonomy captures best the diversity of motor skills with sixteen categories characterized according to the environmental context (*stationary/nonstationary* and *with/without intertrial variability*) and skill function (*body stability/transport* and *object/no object manipulation*). Together, Fleishman’s [23, 24] and Gentile’s [25] taxonomies of human abilities and skills contextualize the focus of and mark out the practical dimension of SRs. We resume their discussion in Sections 3 and 4, where we exemplify SRs and the ability-mediating design approach.

3 SENSORIMOTOR REALITIES

Sensorimotor abilities result from sensorimotor integration [20, 22], where sensory information is processed to generate motor responses. Sensorimotor abilities, as the basis for motor skills [46], are determined by the anatomy of the human body and the cognitive evolutionary advantage of learning by interacting with the world. Next, we adopt a principled approach to introduce SRs as a distinct type of reality in the XR landscape with a focus on sensorimotor abilities.

3.1 Principles of SRs

We capitalize on the heterogeneity of human sensorimotor abilities [4, 46, 103], the diversity of XR worlds [5, 6, 49, 52, 78], and the essential quality of the process of mediation from computer-mediated reality environments [47, 48] to introduce three principles that contour SRs as a distinct concept in the XR landscape:

P₁: *The relativity principle of sensorimotor realities*. Human abilities vary in time and place and, generally, in the context in which the world is perceived and interactions with the world take place, which makes sensorimotor abilities and the skills they enable *relative* in nature. This fact represents the scope of investigation of individual differences [4] in Psychology and is at the core of ability-based design [102, 103] in Human-Computer Interaction. From the computer-mediated reality perspective, perceptions and motor responses contour realities that are also relative in nature. Thus, this principle states that each of us experiences a variety of sensorimotor realities.

⁴Fleishman’s [24] perceptual-motor abilities is what we call sensorimotor abilities in this work to reflect the process of sensorimotor integration [22].

P₂: *The many worlds principle*. SRs focus on interactive experiences in worlds representing diverse mixtures of the physical, virtual, and imaginary, where sensorimotor abilities are needed.

P₃: *The mediation principle*. SRs focus on ability mediation implemented with wearable devices and smart environments. Complementary to the goals of assistive technology (i.e., increase, maintain, and improve functional capabilities [1] and independence [104] for overcoming barriers to societal participation [30]) and of adaptive systems that seek to provide the best match to users’ abilities by design [102, 103], mediated sensorimotor abilities enable new experiences and are compatible with both assistive technology and ability-based design.

Principle P₁ acknowledges that our sensorimotor abilities vary due to many factors [8, 12, 71, 75, 85], leading to different realities of what we perceive and how we interact with the world in context. Based on this observation, principle P₂ highlights that any approach to designing environments, worlds and, ultimately, realities should take into account the heterogeneity of users’ sensorimotor abilities, but also the heterogeneity of computer-supported worlds. Principle P₃ provides a practical means to implement SRs as a form of computer-mediated reality delivering mediated abilities via devices that are worn (and, thus, in contact with the parts of the body featuring sensory and/or motor functions) and environments (to control the external factors affecting sensorimotor abilities). Based on these principles, we introduce the following operational definition for SRs:

Definition: Sensorimotor Realities (SRs) are dynamic, continuously changing manifestations of the reality subjectively experienced by a computer system user as the result of associating sensory perception and motor action that are mediated by wearable devices and smart environments.

Following this definition, three concepts emerge as key for SRs:

1. *The individual in context*. As sensorimotor abilities vary between and within people, SRs are centered on the individual [27] and connect with ability-based design [102, 103], where designers create interactive systems that match and adapt to users’ abilities in context. Following Dey [18], context is any information that characterizes the situation of a person, place, or object relevant to the interaction between a user and a system. In SRs, context is specified by the *environmental context* and *skill function* dimensions of Gentile’s [25, 46] taxonomy.
2. *The world*. The ways in which the world is perceived via the human senses and in which motor action is used to interact, manipulate, and model the world determine diverse manifestations of SRs. The world can be synthesized, mediated, or supported by computer technology from simple cues to understand, navigate, and interact with the world [43, 106] to complex sensitive, adaptive, and responsive designs of smart environments [13]. Of a particular interest is ambient media [33, 101] that define the communication of information in ambient intelligence environments [45]. Azuma’s [6] perspective on AR as a new form of media to address the experiential challenge of hybrid environments, and a recent work [91] that highlighted the similarities and overlap between the philosophies and visions of computing of augmented/mixed reality and ambient intelligence environments.
3. *The implementers*. Devices that are worn, affixed to the body, or in contact with the body can mediate sensing and motor action from the intimate, personal space of the user. Sensors, devices, and systems from the environment can achieve a similar goal from the user’s peripersonal and extrapersonal space. On-body devices come in a myriad of form factors, functionality, and features, from finger and hand augmentation devices [74] to exoskeletons [73], wearable robotics [17],

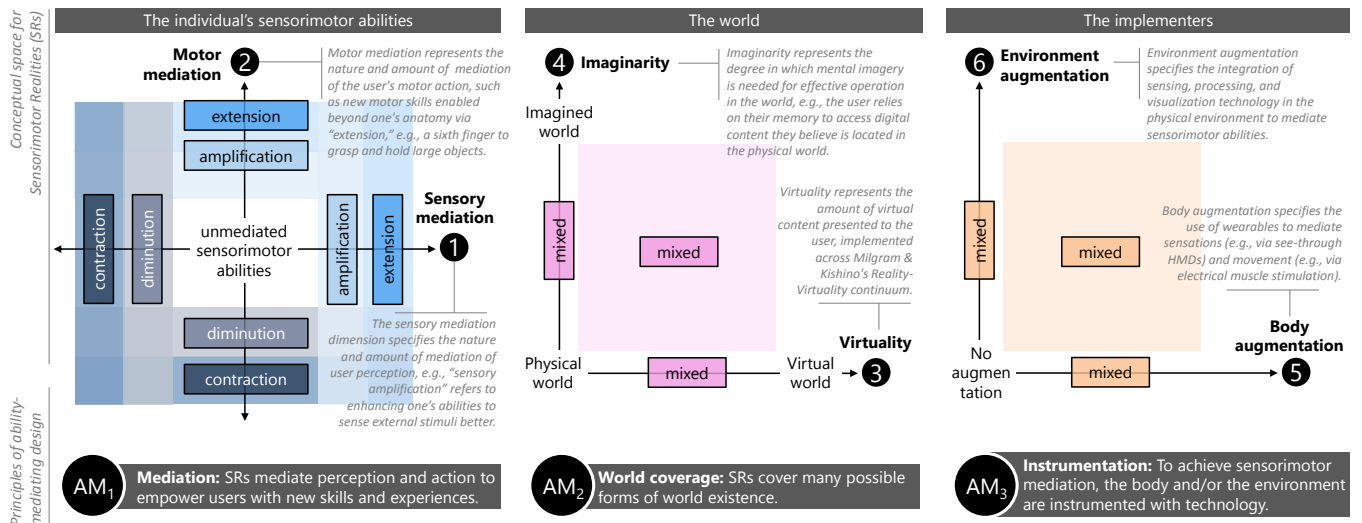


Figure 2: Six-dimensional conceptual space for SRs. *Notes*: axis ③ is Milgram and Kishino's [52] Reality-Virtuality continuum, axes ②① define Mann's [47] mediated reality XYR, and axes ⑤ and ⑥ connect SRs with wearable computing and smart environments [13, 14]. At the bottom, the three principles of ability-mediating design, AM₁ to AM₃, are shown in correspondence with the relevant dimensions of the SRs conceptual space.

and e-tattoos [35], to mention a few examples. Unlike other types of computing devices, wearables are always-available and always-on and, thus, facilitate the disappearance of technology from perception [13] by tight integration on and with the body. In conjunction, smart wearables and environments offer new opportunities for mediating sensorimotor abilities towards more accessible interactive experiences [91].

Noteworthy, all of the reality concepts discussed in Section 2.1 share the same implementers, represented mostly by mobile and wearable devices, e.g., HMDs used to render virtual content in VR and MR. SRs are equally supported by such devices, but also by smart environments [13, 14, 91] to address the variety of factors external to the body that affect sensorimotor abilities. However, the distinctive feature of SRs with respect to other XR concepts lies primarily with the focus on sensorimotor abilities and their mediation, for which we provide next a specific theoretical conceptualization.

3.2 A Conceptual Space for Sensorimotor Realities

Based on the three definitory principles contouring SRs, we introduce a conceptual space with six quality dimensions to address mediation of sensorimotor abilities in mixed worlds (see Figure 2):

D₁: The *sensory mediation* dimension specifies the nature and amount of mediation of user perception, for which we distinguish among *amplification*, *extension*, *diminution*, and *reduction*. *Sensory amplification* refers to enhancing the abilities to sense external stimuli, e.g., increased color perception with see-through glasses [39]. *Sensory extension* refers to enhancing abilities beyond the possibilities offered by the human anatomy and biology, e.g., seeing in the thermal domain [2]. Opposed to amplification, we identify *sensory diminution*, where one's sensory abilities are purposely worsened, e.g., the Cambridge Simulation Glasses [89] provide insights to designers into the effects of vision impairment on product use. Opposed to extension, we identify *sensory contraction*, where an entire sensory ability is refused to the user, e.g., training with simulated hearing loss [65]. These categories are ordinal, e.g., extension follows amplification, with loosely defined boundaries, and what is important is the nature and amount of the mediation. The sensory axis is illustrated generically in our space and can be instantiated, depending on the system, for specific senses including visual [2], aural [7], or tactile [92] mediation. The origin of the D₁ axis denotes no sensory mediation.

D₂: *Motor mediation* represents the nature and amount of mediation of the user's motor action, for which we distinguish among *amplification*, *extension*, *diminution*, and *contraction*. During *amplification*, an existing motor ability is enhanced, e.g., an exoskeleton that assists hand grips [83], lifting heavier objects than normally possible [73], or electrical muscle stimulation to respond faster to world stimuli [36]. With *extension*, new motor skills are enabled beyond one's anatomy, e.g., a sixth finger to grasp and hold large objects [62]. *Diminution* and *contraction* restrict the limits of motor action either by reducing or refusing a motor ability altogether. For example, age suits [40] enable designers to experience navigating the world as many older adults must, soft constraints [64] correct for legacy and performance biases by penalizing movement during gesture elicitation, hand exoskeletons [55] limit grasping movements to deliver the experience of how other users grasp, and wrist braces [26] prevent rotation of the wrist for the treatment of the carpal tunnel syndrome. The motor mediation axis is illustrated generically in our space and can be instantiated for any body part. The origin of the D₂ axis denotes no mediation.

D₃: *Virtuality* represents the amount of virtual content presented to the user. It is implemented with Milgram and Kishino's [52] continuum with the physical world at one end and the virtual world at the other. Prior work has shown that interacting with virtual content determines variations in sensorimotor abilities when grasping virtual objects [16], illusions of nonexistent limbs [70], and fosters adaptation to new laws of physics [11].

D₄: *Imaginarity*⁵ represents the degree in which mental imagery is needed for effective operation in the world. For instance, imaginary interfaces [28] are screen-less devices that enable spatial interaction without visual feedback. The user relies on their memory [67] to access digital information they believe is located in the physical world, e.g., digital vibrons [92] manifest their presence with vibrations on the user's finger. In imaginary gaming [7], players receive information about an imaginary ball by watching each others' movements and following auditory feedback about who has received the ball. On a general note, Turner [86] argued in his exposition of imagination and technology that all digital technologies engage the imagination, including the metaphors used in interacting with computers.

⁵A term we borrow from physics [32]: the condition of being imaginary.

D₅: *Body augmentation* specifies the use of wearables to mediate sensations, e.g., via HMDs [39], and movement, e.g., via electrical muscle stimulation [44]. We see this dimension as a continuum ranging from the no use of devices to increasingly more complex networks of body sensors and actuators [37].

D₆: *Environment augmentation* specifies the integration of sensing, processing, and visualization technology in the physical environment to mediate sensorimotor abilities. Examples include video projections [94], auditory feedback [7], dynamic, adaptive, and shape changing furniture [96] that assists the user to reach for and manipulate objects, and physical telepresence [42] mediated by a reconfigurable environment.

Figure 2 shows these dimensions organized in groups of two, also called “domains” [9] in the theory of conceptual spaces to refer to sets of dimensions that inherently belong together, as follows. Sensory and motor mediation ($D_1 \times D_2$) integrate to specify changes in sensorimotor abilities (in relation to the principle P_1 of SRs), the virtual and the imaginary ($D_3 \times D_4$) complement the physical with various world mixtures where sensorimotor abilities are applied (principle P_2), and the degree of body and environment augmentation ($D_5 \times D_6$) specifies the implementers of ability mediation (principle P_3). The origin of the SRs space denotes the physical world with no augmentation, where one’s sensorimotor abilities are not mediated by computer technology. Note that axes D_1 and D_2 allow negative interventions as well, i.e., diminution and contraction, while the other axes interpolate between dichotomous concepts: physical-virtual, physical-imaginary, and unaugmented-augmented, respectively.

3.3 Ability-Mediating Design

Due to their focus on sensorimotor abilities, SRs connect with ability-based design [102, 103] on the *ability* and *accountability* principles. Moreover, the supporting technology of SRs—smart wearables and environments—can be readily employed to implement the *adaptability*, *performance*, and *context* principles [102, 103]. However, the goal of SRs is fundamentally different from that of ability-based design due to the focus on *the process of mediation* in computer-mediated reality. In SRs, sensorimotor abilities are amplified, extended, diminished, or contracted in worlds that are mixtures of the physical, virtual, and imaginary. The aspect of mediation, key to repurposing existing abilities to enable skills and interactive experiences in such worlds, is not captured by the goals nor the principles of ability-based design. Thus, mediation specifies a new scope in need of a specific design approach that is complementary to ability-based design. We call this approach *ability-mediating design*.

Based on our definitory principles adopted for SRs, we propose three design principles for ability-mediating design (AM₁ to AM₃) to address *sensorimotor abilities that undergo a process of mediation*:

AM₁: *Mediation* means that SRs mediate perception and action to empower users with new skills and experiences, according to the domain $D_1 \times D_2$ of the SRs conceptual space.

AM₂: *World coverage* means that SRs cover many possible forms of world existence: physical, virtual, imaginary, and combinations thereof ($D_3 \times D_4$), representative of the physical reality, computer worlds, and mental imagery.

AM₃: *Instrumentation*. To achieve sensorimotor mediation, the body and/or the environment are instrumented with computer technology ($D_5 \times D_6$). Devices designed to be worn are in contact to the body parts that feature sensory and/or motor functions to enable mediation within the self (e.g., an exoskeleton that assists hand grips), while instrumentation of the environment enables mediation external to the self (e.g., intelligent lighting systems).

These principles specify ability-mediating design by reflecting the dimensions of the SRs space with a focus on sensorimotor abilities. Applying the principles in practice is a two-stage workflow.

A process of task analysis [46] (p. 62) is first applied to identify abilities underlying a specific motor skill with matches from Fleishman’s [24] and Gentile’s [25] taxonomies. For example, walking on a treadmill at different speeds while using a smartphone is a skill characterized by a *nonstationary environment* (the treadmill), *intertrial variability* (different speeds), and *object manipulation* (the smartphone). The corresponding sensorimotor abilities from Fleishman’s [23, 24] taxonomy are *multilimb coordination* for walking, *rate control* to adapt to the treadmill changing speeds, *finger dexterity* for holding the smartphone steadily, and *aiming* for interacting with the smartphone’s touchscreen. Walking in VR while interacting with virtual objects via handheld controllers is another example of a motor skill that builds on similar sensorimotor abilities.

Once the required/existing abilities have been identified, the dimensions of the SRs space are employed to inform mediation design. In each domain of two dimensions, transitions between regions representing different states of sensorimotor mediation can occur freely. For instance, Milgram and Colquhoun [51] described how journeys can take place along the Reality-Virtuality continuum, which is our dimension D_3 . Imaginary gaming [7] combines auditory feedback with an imagined ball (D_4) and digital vibrons [92] combine haptic feedback with imagined presence (D_4). Toyama and Hashida’s [84] hand exoskeleton (D_5) is detachable and, after having registered the fingers’ movements, can replicate those movements independently to serve as a tool in the user’s environment (D_6). A smartwatch can morph into different forms [38] across dimension D_6 after having been detached from its strap, from a shoe sensor to a bike-mounted device assisting with navigation to a baby monitoring device. Inversely, objects from the environment (D_6), such as miniature robots, can turn into wearable devices [17] across dimension D_5 . Just like ability-based design [102, 103], one important application of SRs lies with accessible computing, which we exemplify next.

4 EXAMPLE

To illustrate the principles of ability-mediating design and the dimensions of SRs, we discuss an example. Our goal is not to present a full-fledged system, but to discuss comparatively the strengths of ability-based and ability-mediating design in the context of a practical example and to demonstrate the use of the SRs space.

4.1 Context

A recent trend in home entertainment is to leverage XR technology to deliver TV viewers with new experiences, from virtual TV screens displayed anywhere in the room to actual immersion in the action of a movie; see [58, 61, 66, 93, 95] for recent developments and trends in Augmented Reality TV (ARTV). Compared to conventional television, ARTV features more content and interactivity, but also increased affordability, e.g., a TV screen of any size can be placed on any wall in just a few clicks [90] as TVs become “a \$1 app, instead of a \$500 piece of equipment” (Mark Zuckerberg at the Facebook F8 conference) [82]. These new home entertainment environments mediate perception, e.g., new visual experiences delivered by virtual content floating in the room, but also motor action when the users immerse in the action of the movie. However, the impact of such changes in the home entertainment landscape has not been examined for people with sensory or motor impairments. For example, people with upper-body motor impairments experience accessibility challenges when interacting with conventional television because of the many ability assumptions subsumed in the design of TV remote controls. These include assumptions about the ability to grab the remote, hold it steadily, point it in the direction of the TV, move a finger to aim for one of the tiny buttons on the remote, apply pressure to press the buttons, and lift off the finger fast enough to avoid sending the command twice. Recent studies [87, 88] have documented coping strategies employed by people with motor impairments to use the conventional remote controls shipped



Figure 3: Photographs taken during the design session with Andrew: (a-c) accessibility challenges revealed when using a smartphone, mouse, and TV remote control because of the weight and form factors of these devices; (d-f) failed attempts to perform the “air tap” HoloLens gesture; (g) successful use of the HoloLens Clicker; (h) hand pose demonstrating holding an imaginary TV remote control; (i) an imaginary TV remote control for two hands; (j) finger augmentation with a 3-axis accelerometer and a 3D-printed ring; (k) various feedback modalities (airflow, vibrations, and thermal) to sustain the mental imagery of the imaginary remote control; and (l) accurate aiming ability for pinpointing a Vicon marker on the wall.

with their TVs, and revealed that assistive technologies in the form of custom remote controls or smartphone apps were scarcely used. However, ARTV features new interaction modalities that replace the TV remote control, such as gesture and voice input, implicitly supported by specialized devices, such as HoloLens. Thus, new opportunities arise for designing ARTV environments that capitalize on users’ abilities towards more accessible home entertainment.

4.2 Application

We developed a HoloLens application that displays a virtual TV screen, following one of the ARTV scenarios from [58]. To keep our example simple and focused, we implemented only one function: repositioning of the TV in the room, e.g., on the walls or in mid-air. This function is characteristic of the high flexibility of content and form in ARTV, whereas repositioning a physical TV in the physical world is difficult because of room architecture and furniture constraints. This feature is also convenient to access TV from any location and viewing direction and, thus, useful for limited mobility conditions. To reposition the virtual TV screen, we used the HoloLens gaze-and-commit⁶ model: following head-gaze targeting, the standard HoloLens “air tap” gesture, i.e., a pinch between the index and the thumb,⁷ commits the virtual TV to the new location.

4.3 Motor Skills and Abilities

The first stage of applying ability-mediating design is the identification of motor abilities and skills. According to Gentile’s [25] taxonomy, the task of repositioning a virtual TV screen requires a motor skill that is *stationary*, has *intertrial variability*, requires *body stability*, and involves *object manipulation*; see Subsection 2.3. A task analysis process [46] for the identification of constituting abilities from Fleishman’s [24] taxonomy indicates the need of *finger dexterity* abilities for performing the air tap gesture, *manual dexterity* for moving the arm, *control precision* to indicate with the arm the new location for the virtual screen, and possibly *rate control* abilities for motor adjustments of the arm relative to changes in speed and direction of the moving virtual screen following head-gaze targeting.

⁶<https://docs.microsoft.com/en-us/windows/mixed-reality/design/gaze-and-commit>

⁷<https://docs.microsoft.com/en-us/dynamics365/mixed-reality/guides/operator-gestures-hl2>

4.4 User Description and Preliminary Findings

Andrew (pseudonym used for anonymity purposes), 27 years old, has phocomelia,⁸ a very rare congenital condition occurring in just 0.62 births per every 100,000 people [15] that involves malformations of the arms and legs. Andrew’s upper limbs did not form fully, causing him to experience accessibility challenges when grabbing, manipulating, and using everyday objects and digital devices.

We asked Andrew to participate in an interview and a collaborative design session involving our HoloLens application to identify practical input solutions best suited to his motor abilities. We started with an informal discussion to collect information about his impairments (using the categories from [21]) and TV watching habits. Andrew reported slow movements, low strength, difficulty gripping, difficulty holding, and difficulty controlling distance, e.g., he reported his smartphone too heavy to hold (Figure 3a), the need to adopt a special hand pose to use the mouse with one finger supported on the table (Figure 3b), and the need to use both hands to hold the TV remote control steadily (Figure 3c). Andrew reported watching conventional television between two and three hours each day.

We presented HoloLens to Andrew, a device he had never used before our study, demonstrated our ARTV application, and asked him to interact with the virtual TV screen. We found that Andrew could not perform the air tap gesture, because his hands did not position well in the gesture frame of the HoloLens HMD; see Figures 3d to 3f. Other HoloLens gestures,⁹ such as the bimanual “start” gesture, were equally problematic because of his short arms, difficulty to rotate the wrists, bring the two hands together, and missing fingers. We continued our session with ability-based design solutions to make the HoloLens ARTV application accessible to Andrew.

4.5 Ability-Based Design

According to the principles of ability-based design, the ARTV application and/or HoloLens adapt to match Andrew’s abilities. One solution, readily available with HoloLens, was to add speech input to our application, which we implemented for the gaze-and-commit model with two discrete commands, “Move this” and “Stop move.” Another solution, also readily supported by HoloLens, involved

⁸World Health Organization, International Classification of Diseases 11th Revision, LB99.4 Congenital absence of upper arm or forearm with hand present, <https://icd.who.int/browse11/l-m/en#/http://id.who.int/icd/entity/1157109358>

⁹<https://docs.microsoft.com/en-us/hololens/hololens2-basic-usage>

the Clicker,¹⁰ a handheld device enabling button-based interactions: in the gaze-and-commit model, two consecutive clicks start and stop the repositioning of the virtual TV screen. With these updates, our application was listening for Andrew’s input on three distinct channels corresponding to different sensorimotor abilities. Andrew successfully managed to reposition the virtual TV screen in the room using both speech and click-based interactions. He had no major difficulties holding and using the Clicker, even though his thumbs are missing (Figure 3g), since the Clicker works even when the gestures are outside the HoloLens gesture frame. Andrew rated the Clicker design “very suited” to his abilities (a 5 rating on a 5-point Likert scale) and speech input as “suited” (4/5). While our implementation made use of features that HoloLens already supported, ability-based design can equally be implemented by adding new sensors and/or software modules that will do the work of the system adapting to the user. For example, a custom HoloLens version could integrate a video camera facing downwards, and a configurable hand tracking model¹¹ could be used to recognize Andrew’s air taps and other gestures that Andrew can perform easily and comfortably. Next, we illustrate the ability-mediating approach to arrive at other design solutions inspired by the concept of mediation and the SRs space.

4.6 Ability-Mediating Design

With ability-mediating design, the focus is on mediating abilities to arrive at new skills and experiences enabled by the mediation. In the following, we inform several design solutions for the ARTV application by using the dimensions of the SRs space (Figure 2). First, we position our application in this space at the origin of the domain $D_1 \times D_2$ (no mediated abilities in the original version), in the first part of the D_3 axis (the application falls in the AR region of the Reality-Virtuality continuum [52]), and on the D_5 axis (a HMD is worn to render the virtual TV screen). The unused axes D_4 and D_6 of the SRs space can be exploited to generate new designs.

We started with the imaginarity axis (D_4) and proposed Andrew the concept of an imaginary TV remote control. The advantage of such a design is that it does not require gripping, holding, and manipulating a physical device (see our previous discussion from Subsection 4.1 about the accessibility challenges of physical TV remote controls), while it can be implemented with mid-air gesture input, one of the three modalities already available in our ARTV application. Unlike prior work that mimicked the use of actual physical devices [19, 79], we told Andrew that he could imagine any form factor for the imaginary TV remote control that would best fit his fingers, hand grasps, and arms reach. We then asked Andrew to show us gestures that were comfortable for him to operate the imaginary remote control. He suggested two gestures involving two fingers of his dominant hand consisting of up-down and left-right movements for the first and second finger, respectively; see Figure 3h for an illustration of the hand performing the gestures. Both these gestures were outside the HoloLens gesture frame, just like air tap from our previous design, so we needed another sensing solution to capture them. By implementing the design principle AM_3 (instrumentation) and the D_5 axis of the SRs conceptual space, we proposed a finger-augmentation solution, for which we rapidly prototyped a simple device in the form of a 3D-printed ring enclosing a 3-axis accelerometer connected to a laptop’s USB port; see Figure 3j. Since only one gesture was needed in our gaze-and-commit interaction model to reposition the virtual TV screen, one finger-augmentation device was

sufficient to our purpose. This design addresses Fleishman’s [24] *finger dexterity* ability that is mediated (according to the design principle AM_1) by the ring device on axis D_5 (design principle AM_3 , instrumentation) to enable the motor skill of operating a new remote control (axis D_2) that has the ideal form factor for Andrew’s fingers and hand and exists only in the form of Andrew’s mental imagery (axis D_4 and the world coverage design principle AM_2). An alternative design that we explored, following our preliminary observation that Andrew holds more steadily TV remote controls by employing both hands, regards the mediation of Fleishman’s [24] *multilimb coordination* ability. In this design, Andrew operates an imaginary TV remote control with both hands; see Figure 3i for an illustration. Andrew proposed gestures for each hand, similar to the gestures described above, to be performed at each end of the bimanual imaginary remote control. We did not follow through these designs to implement a gesture recognizer for the two imaginary TV remote controls, but several approaches are available for recognizing finger movement from accelerometer data [72, 81, 97]. Instead, we preferred to continue the session by examining more options to mediate the perception of holding the first imaginary remote control (the D_1 axis in the SRs space). To this end, we presented several feedback modalities to Andrew, which we rapidly prototyped with an Arduino Nano (16MHz ATmega328, 2KB SRAM, 32KB flash memory) and a thermoelectric cooling Peltier plate (TEC1-12706 model, $V_{max}=12V$, $Q_{cmax}=27W$) for thermal feedback [100], a small fan ($30 \times 30 \times 10mm$, 5V, 7000RPM $\pm 10\%$) for airflow feedback [41], and a vibration motor (3V DC 1027 flat, 12000 ± 2500 RPM) for vibrotactile feedback [69] to sustain the mental imagery of the remote controls; see Figure 3k. Andrew’s preferences for these output modalities, expressed on a 5-point Likert scale, were in decreasing order: thermal (4/5), airflow (3/5), and vibrotactile (2/5) feedback.

Another design solution exploits the D_6 axis (environment augmentation). One characteristic feature of smart environments is tracking users and objects and making inferences based on that information. In Human-Computer Interaction, this feature has been exploited to enable proxemic [50] and peripheral [68] interactions. There are many ways to implement user tracking in a smart environment [54]. In our design session, we used a Vicon motion tracker¹² that reports the location of reflective markers (14mm pearl hard markers, M4 threaded on a 17mm plastic base) with sub-millimeter accuracy. We demonstrated marker tracking to Andrew and presented a corresponding solution for the ARTV application that instruments the environment with such markers as placeholders for the virtual TV screen. In this scenario, Andrew places a marker in each room where he wants the TV to be automatically displayed while he is in that room. This task requires the *aiming* ability from Fleishman’s [23] taxonomy to position a marker at the desired location on a wall or piece of furniture. To evaluate this ability, we asked Andrew to place a marker on a target on the wall, which he was able to do accurately and precisely over multiple trials by holding the marker steadily between the two middle fingers of his right hand; see Figure 3l. Compared to the previous designs, some flexibility is lost in terms of the possible locations where to place the virtual TV screen, including in mid-air, but compensated by the extra precision gained for TV positioning vs. the error-prone gesture and head gaze tracking that we observed with the previous solutions. This design implements mediation of Andrew’s *aiming* ability (the design principle AM_1 and the D_2 axis, motor mediation) that, by means of environment augmentation (design principle AM_3 and the D_6 axis), supports the task of pinpointing a virtual TV screen at preferred locations in the physical environment. At the end of the session, Andrew rated the two designs. In decreasing order of preference, these were: physical markers in the environment (5/5, the same rating as the HoloLens Clicker solution) and single-hand imaginary TV remote control (4/5, similarly to speech input).

¹⁰<https://docs.microsoft.com/en-us/hololens/hololens1-clicker>

¹¹Andrew has four fingers on one hand, three fingers on the other, and no thumbs. Articulated hand tracking from HoloLens provides a 25-joint skeleton with five joints for the index, middle, ring, and little fingers, four joints for the thumb, and one for the wrist; see <https://docs.microsoft.com/en-us/windows/mixed-reality/develop/native/hands-and-motion-controllers-in-directx>.

¹²<https://www.vicon.com>

4.7 Summary

Ability-based [102, 103] and ability-mediating design have different goals, supporting models, and corresponding approaches. By applying both in our example, we were able to arrive at several accessible design solutions for Andrew, but from different perspectives. Note the similar ratings between these solutions, but the different principles underlying the two design approaches that we used to arrive at these solutions. While we were interested in making the HoloLens system *adaptive* to match Andrew's abilities when applying ability-based design, our focus, perspective, and frame of thinking shifted to *mediating* Andrew's existing abilities when we generated solutions by applying the principles of ability-mediating design and the quality dimensions of the SRs conceptual space. This example shows how new design solutions emerge from the shift in perspective enabled by SRs and the corresponding conceptual space as a practical means to guide such designs, and also highlights the distinct scope and, thus, complementarity of ability-based and ability-mediating design. Next, we gain perspective by providing a vision and a research roadmap for SRs and ability-mediating design.

5 A VISION FOR SENSORIMOTOR REALITIES

In the context of computer-supported realities, SRs stand out distinctly with their explicit focus on sensorimotor abilities, a distinct conceptual space, and the unique perspective of the ability-mediating design approach. SRs describe worlds that support, enhance, or even diminish and refuse sensorimotor abilities altogether. In this context, SRs bring the perspective that human life can be seen as a series of varying sensorimotor abilities that enable different realities in terms of what humans perceive and how they act following those perceptions. Consequently, SRs fill a distinct need in the XR landscape to characterize systems that mediate sensorimotor abilities, but also to foster new designs of such systems. Next, we propose three main directions for future research on SRs and ability-mediating design:

1. *SRs enable designs of accessible worlds at the intersection of XR, ambient intelligence, and wearable computing.* The conjoint operation of the two supporting technologies of SRs—smart wearables and environments—is interesting to examine further in the context of XR accessibility [105]. We suggest that XR should be considered in the paradigm of integrating the technologies of ambient intelligence and wearable computing [14]. In this vein, we propose complementing the original goal of AR to support intelligence amplification [5] and of XYR to enable humanistic intelligence [47] with SRs that focus on sensorimotor abilities. At the intersection of these areas of research, new opportunities emerge for designing accessible worlds to sustain (via XR assistive technology), match and adapt to (via ability-based design), and mediate (via SRs and ability-mediating design) various user abilities.
2. *Explore application opportunities for SRs.* We expect SRs to foster applications in training and education (e.g., for learning new motor skills), rehabilitation (for regaining lost abilities), and assistive technology (for providing support for existing abilities) by addressing diverse user categories with ability-mediating design and the dimensions of the SRs conceptual space. Also, interesting opportunities for SRs regard devices, applications, and systems for the delivery of new multisensory experiences [57], e.g., in video games and home entertainment, supported by ability mediation in the form of *amplification* and *extension*, but also *reduction* and *contraction* (see Figure 2) towards a diversity of interactive experiences in mixed worlds.
3. *A vision for SRs.* In our vision, SRs picture a future world in which users can access on demand a diversity of computer mediation of their sensorimotor abilities in context, likely without even paying attention when transitioning between one set of skills to another. According to this vision, we anticipate

two additional principles of ability-mediating design following future developments in wearable computing and ambient intelligence. The first is *Ubiquity of Sensorimotor Mediation*, which means that new skills will be available where and when they are needed to make users more effective at interacting in and with the world, either physical, virtual, imaginary, or mixed versions thereof. According to this principle, transitioning through various SRs throughout one's day, e.g., from different skills needed in the workspace, at home, or during a field trip, could be so ubiquitous that no one will even notice it as a feature of computer-mediating technology. The ubiquity premise is based on (i) the prevalence expected for wearables in the foreseeable future, (ii) the visions of ubiquitous computing and ambient intelligence [13, 99], and (iii) the overlap between the philosophies of augmented reality and ambient intelligence environments [91]. Ubiquity also implies that mediation of sensorimotor abilities will dissolve in human behavior, a characteristic of the vision of technology enabling smart environments and an opportunity for wearable computing, where technology disappears from user perception [99]. The other principle that we envision is *Integration*, which means that computer-mediation technology may physically integrate bodily experience at the level of physical receptors and motor systems from the user's body and, thus, be perceived as one with the body. This aspect has ethical implications that could be addressed with the philosophical paradigm of transhumanism [10, 60, 77], an interesting future work for SRs.

6 CONCLUSION

We introduced Sensorimotor Realities as a new concept with distinctive characteristics in the XR landscape and a technology-agnostic framework to support conceptualization, characterization, and design of interactive computer systems that mediate sensorimotor abilities to enable new skills and interactive experiences in a diversity of mixed worlds. By explicitly focusing on the act of mediation from computer-mediated reality and the heterogeneity of human sensorimotor abilities, SRs enable a new design paradigm in which the focus is on ability mediation. We also outlined a vision for SRs, where a myriad of sensorimotor skills and corresponding interactive experiences in and with mixed worlds become readily available to users as a direct consequence of world designs primarily centered on mediating existing sensorimotor abilities. More information and resources about SRs, e.g., the source code of the HoloLens application from the study presented in this paper and related publications, are available from the SRs home page: <http://www.eed.usv.ro/mintviz/projects/SensorimotorRealities>.

ACKNOWLEDGMENTS

The author would like to thank Cristian Pamparău for the development of the HoloLens application and Laura-Bianca Bilius for the Arduino prototype used in the study reported in this paper. 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 PNCIDI III.

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