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A Systematic Literature Review of Embodied Augmented Reality Agents in Head-Mounted Display Environments

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Abstract

Embodied agents, i.e., computer-controlled characters, have proven useful for various applications across a multitude of display setups and modalities. While most traditional work focused on embodied agents presented on a screen or projector, and a growing number of works are focusing on agents in virtual reality, a comparatively small number of publications looked at such agents in augmented reality (AR). Such AR agents, specifically when using see-through head-mounted displays (HMDs) as the display medium, show multiple critical differences to other forms of agents, including their appearances, behaviors, and physical-virtual interactivity. Due to the unique challenges in this specific field, and due to the comparatively limited attention by the research community so far, we believe that it is important to map the field to understand the current trends, challenges, and future research. In this paper, we present a systematic review of the research performed on interactive, embodied AR agents using HMDs. Starting with 1261 broadly related papers, we conducted an in-depth review of 50 directly related papers from 2000 to 2020, focusing on papers that reported on user studies aiming to improve our understanding of interactive agents in AR HMD environments or their utilization in specific applications. We identified common research and application areas of AR agents through a structured iterative process, present research trends, and gaps, and share insights on future directions.

CCS Concepts

• *General and reference* → *Surveys and overviews;* • *Computing methodologies* → *Mixed / augmented reality;*

1. Introduction

Embodied agents have been studied and used for decades across a wide range of research and application domains. Their widespread use goes back to early console and computer games where embodied agents were programmed in the form of non-player characters to exhibit some level of interactive behavior with the user [MS09]. Although entertainment is still one of the most common applications of such agents, their roles and uses have grown extensively over the years. Technological advances in the areas of artificial intelligence and computer graphics allowed for a more reliable, realistic, and intelligent representation of such agents [Dig19, Mag19, Mic18]. These advances made embodied agents feasible for domains such as simulation and training, healthcare, and education, among others, where the use of real-world counterparts would be cost-prohibitive, dangerous, or limited in their level of fidelity, robustness, and engagement [DHN*18, JAM*14, DAB*14, MDC18].

Most previous research on embodied agents was focused on non-immersive display setups (e.g., TV screens), followed by some examples of work on embodied agents in virtual reality (VR) setups via head-mounted displays (HMDs) or immersive projection technologies [NKH*18, CGMB20]. However, only a comparatively small number of publications focused on embodied agents in augmented reality (AR) is tied to the use of optical see-through (OST) or video see-through (VST) head-mounted displays (HMDs). Significant advances have been made in the technology of these AR HMDs over the last few years, including, e.g., the Microsoft HoloLens or Magic Leap One, with advances such as SLAM-based tracking and spatial mapping, which made them attractive for a wider audience [WBSS19, KBB*18]. However, dynamic virtual content on AR HMDs, such as embodied agents, still presents many challenges to researchers and practitioners, resulting in critical differences to other forms of agents. Not only do such agents have to be spatially and contextually represented and integrated into existing real-world environments, but they need to provide a means of physical-virtual interactivity, such as showing awareness of real objects as well as exerting influence over the real world. Solving these challenges is a complex task that requires a cross-disciplinary approach [NBB*19].

In this work, we captured previous research focusing on understanding and utilizing AR agents in HMD-based environments, and set out to answer the following research questions:

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- **RQ1:** What are the primary research categories of embodied agents using AR HMDs?
- **RQ2:** What are the common roles where embodied agents are utilized or envisioned using AR HMDs?
- **RQ3:** How have AR agents evolved over the years in terms of their appearance and utilized technology?
- **RQ4:** What areas of AR agent research can benefit from more focused future attention?

There were several application-independent surveys and taxonomies related to AR agents [HCO*11, NBB*19], but the investigation of unique characteristics and opportunities of AR agents in HMD environments is largely missed. To fill the gap and present a comprehensive survey of the field, we conducted a systematic literature review covering the years from 2000 to 2020 using four digital libraries. Through this review, we identified primary research categories, common application areas, and presented insights on areas worthy of further investigation.

The remainder of this paper is organized as follows. We describe our methodology in Section 2, and define our research categories and application areas in Section 3. In Section 4, we present a high-level view of the trends identified in the reviewed papers and go into more detail about the findings of each research category in Section 5. In Section 6, we discuss the findings of the research field collectively and share insights on emerging trends and future directions. We conclude the paper in Section 7.

2. Methodology

We conducted a systematic literature review by adopting several of the core steps of the PRISMA method [LAT*09]. In this section, we go into detail on the steps taken to complete our systematic review.

Our goal for this literature review was to capture previous work that studied embodied AR agents in HMD environments or leveraged them for a specific application. To ensure that a broad scope of related work is identified, we came up with the keywords shown in Table 1 that include our primary criteria of field, agent, and device. We applied these search terms to the four digital libraries of the Association for Computing Machinery (ACM), Institute of Electrical and Electronics Engineers (IEEE), Web of Science (WoS), and ScienceDirect (SD). Our search process was applied to all fields within each library and was restricted to previous work published in English from 2000 to 2020. The search was completed on August 2–3, 2020. Figure 1 shows the number of papers at different stages of our search, screening, tagging and reviewing processes.

Due to restrictions in the number of search terms and Boolean operators allowed for the IEEE and SD digital libraries, we adjusted our search strategy for these specific libraries. For IEEE, to adhere to the maximum of 40 search terms and 15 search terms per clause rule, we repeated our search three times so that every time less than 15 search terms were used for the agent-specific ones (see Table 1). This was due to the fact that the agent clause was the only one with more than 15 search terms. Since SD only allows for use of 8 Boolean operators, we did not use the device-specific search terms (see Table 1) and for the remainder of our search terms followed a similar approach as for the IEEE library by dividing the

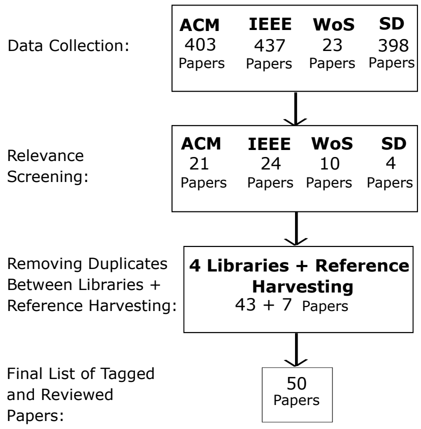


Figure 1: *Diagram of our systematic review process.*

agent-specific search terms to make sure every time only 8 Boolean operators were used. These steps resulted in 403 papers in ACM, 437 papers in IEEE, 23 papers in WoS, and 398 papers in SD.

In the scope of this literature review, we focused on AR agents as embodied entities presented on an AR HMD that are capable of facilitating a two-way interaction with the user through one or multiple modalities, and used this definition during the scanning phase. Accordingly, papers that studied AR agents or utilized them in specific applications through user studies in HMD-based environments were considered relevant. We further used the following exclusion criteria to remove publications that were not in line with our goals:

- Work that did not contribute to the understanding or advancement of AR agents using HMDs.
- Work that did not include a user study.
- Work that did not specify the interface or modalities for an interactive experience between users and AR agents.
- Work that was published as a book, book chapter, or thesis.

The lead author of this paper scanned all papers using the exclusion criteria described above. This process resulted in 43 relevant publications. After this first top-down phase, we then performed an additional bottom-up literature search phase, often called reference harvesting [LGH*17], in which we searched the related work sections of the 43 papers and added 7 more publications to our list. We further collected the papers' citation counts via Google Scholar on August 26, 2020 and calculated the average citation count (ACC) for all papers, indicating the average number of citations per year.

To understand the scope of research and applications focused on AR agents and the type of agents and HMDs most commonly used, we determined the following tags during the review phase:

- **Research Category** of AR agents,
- **Application Area** of AR agents (tested or intended),
- **Appearance** of AR agents,
- **HMD Type**.

The descriptions and the identification/tagging process of our research categories and application fields are detailed in Section 3. Five authors of this paper participated in the identification/tagging

Table 1: *Search terms used to identify related papers in this literature survey.*

Search Criteria	Search Terms
Field	("augmented reality" OR "mixed reality")
Agent	AND ("virtual agent" OR "virtual agents" OR "virtual character" OR "virtual characters" OR "virtual human" OR "virtual humans" OR "virtual animal" OR "virtual animals" OR "virtual people" OR "virtual person" OR "virtual persons" OR "virtual crowd" OR "virtual crowds" OR "virtual audience" OR "virtual audiences")
Device	AND ("head-mounted display" OR "head-mounted displays" OR HMD OR HMDs OR headset OR headsets OR hololens OR "magic leap" OR vive OR oculus)

process. Multiple tags per paper were allowed. To ensure that all members had a similar understanding of the different tags, five papers were picked randomly from the initial list of 43 papers and tagged by everyone. Later, we reviewed the tags assigned by everyone for the aforementioned five papers, discussed them together, and refined our tags accordingly. After this process, the papers were shared among our team, tagged, and uncertainties were discussed in a separate session.

Afterward, we divided the 50 papers based on their research category and assigned each category to a team member to provide a more in-depth view of AR agents within that area of research. Members were asked to give priority to publications with an ACC higher than 3, which is in line with the ACC of the 50 papers ($M = 3.28$), and also all papers from 2017 to 2020 regardless of their ACC. We did not consider ACC as a criterion for papers published after 2017, as they had less time to be cited, and they included more than 50% of the total number of our papers.

3. Research and Application Areas

In a top-down process, we used previous relevant literature reviews on the topics of augmented reality [DBLS18, KBB*18], intelligent virtual agents [NKH*18], and social presence [OBW18] to come up with preliminary tags for research categories and application areas. Later, after reviewing the 50 relevant publications, we utilized a bottom-up approach to refine and finalize our tags. For both research and application categories some papers focused on more than one category of research or application area. In these cases, the papers were represented with multiple tags. Hence, the number of tags exceeds the total number of papers.

To identify a paper's application area, we utilized both the tested application in the paper (e.g., healthcare) and the AR agent's motivated use case, which influenced the paper's research questions and the type of the task the AR agent was involved in during the user study. For instance, papers that motivated their AR agent for general interactions but explored the human-agent interaction in a collaborative/assistive task, or papers that motivated their AR agent for collaborative/assistive roles but examined them in general tasks were tagged in the collaborative-assistive application area. Our research categories are defined as below:

- **Visual Representation:** work that investigates the visual qualities of AR agents and the importance of this modality.
- **Displays and Interfaces:** work exploring the effects of display mediums and interfaces for interacting with AR agents.
- **Physical-Virtual Interactivity:** work that investigates the impact of augmenting AR agents to be interactive with the surrounding physical environments.
- **Proxemics:** work that investigates the spatial relationships between AR agents and human users.
- **Behavior and Traits:** work that investigates the influence of AR agents' verbal and nonverbal behavior, personality traits, and characteristics on human-AR agent interaction.

Additionally to these research categories, we tagged the publications by application areas. Since not all publications focused on an application, the number of these tags differ from the total number of publications. Our application areas are defined as:

- **Assistive/Collaborative:** work utilizing AR agents in assistive roles or studied their potential as collaborative partners, such as personal assistants, exercise coaches, or guiding roles.
- **Entertainment and Interactive Media:** work utilizing AR agents for more interactive entertainment-oriented experiences.
- **Healthcare:** work utilizing AR agents to enhance the health of specific populations, or as a teaching tool for healthcare students or professionals.
- **Training:** work utilizing AR agents for training specific skills.

4. High-Level Analysis

In this section, we provide a high-level overview of the 50 papers in terms of HMD type, AR agent type, ACC, research category, and application area. Figures 2 and 3 illustrate the trends for numbers of papers and ACCs in the field.

4.1. General Overview

Overall, we identified 50 papers that studied AR agents or utilized them for specific applications in HMD environments and assessed AR agents' features and/or their system through user studies. The majority of these papers are published from 2017 onward (%58), which is in line with the increased availability and reliability of consumer commercial-off-the-shelf (COTS) or developer edition HMDs. This trend is partly supported by the ubiquity and popularity of voice-only assistants [LRK*19, PTS*17] presenting new opportunities for utilizing AR technology to investigate the influence of embodiment and its implications for such entities.

We classified the HMD types based on the hardware specifications or the system descriptions provided by the papers, and marked those without any specifications or clear descriptions as *unspecified*. Figure 2 shows the different types of HMDs used over the years. OST-HMDs were more common (30 papers) specially in the past four years due to the increasing availability of such devices, with Microsoft HoloLens more commonly used than other devices (23 papers). 19 papers utilized VST-HMDs, most of which were used before 2018.

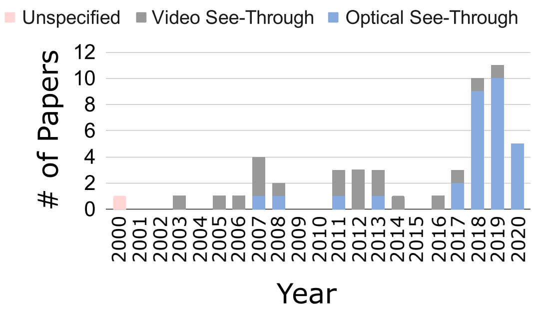


Figure 2: *Types of HMDs utilized in AR agent research per year.*

To address our third research question **(RQ3)**, we explored the different appearances for realizing embodied AR agents. As inspired by robotics literature, the agent's appearance can influence the quality of interaction in terms of emotional connection and trust [SW18]. As expected, the majority of the AR agents studied were designed to have a human-like appearance (39 papers), with fewer examples of AR agents embodied as animals (9 papers) or robots (6 papers). 5 Papers used AR agents embodied as cartoon characters, monsters, or anthropomorphic objects, such as an anthropomorphic sun, which we tagged as *other* (see Figure 3c). Figures 3a and b show AR agent types based on research category and application area. Humanoid AR agents were more commonly used in all research categories and application areas. Interestingly, except humanoid AR agents, animal-like AR agents were the only type studied among all research categories and application areas. Some papers utilized more than one type of AR agent; therefore, the total number of AR agent types is higher than the number of papers. Accordingly, papers with humanoid AR agents have a higher ACC (3.94), followed, by other (2.51), animals (2.19), and robots (1.83) (see Figure 3f). Although AR agents with appearances tagged as other were less common, they lend they higher ACC to two recent papers where in one the AR agent is embodied as a minion [AGTV18] and in the other as a smart home device [WSR19].

4.2. Research and Application

Out of our 50 reviewed papers, 33 either focused on a specific application or motivated their use of AR agents and/or their research questions to address the needs of a certain application. The assistive/collaborative area was the most popular (18 papers), followed by entertainment and interactive media (10 papers), healthcare (8 papers), and training (6 papers). The assistive/collaborative AR agents were utilized or envisioned as personal assistants, lab assistants, navigation guides, virtual coaches, or collaborated with users in search or decision making tasks. Such use cases are in line with current utilizations of intelligent personal assistants, such as Amazon Alexa, Apple Siri, Google Home Assistant, or those envisioned as guides and companions, such as Magic Leap Mica. This area has been cited more frequently than others with an ACC of 2.79, followed closely by the entertainment and Interactive media area (2.69), training (1.67), and healthcare (1.12) (see Figure 3e).

A total of 38 of our 50 papers focused on understanding specific research categories with regards to AR agents and user interactions with systems utilizing AR agents. The remaining 12 papers are not represented here due to their focus on understanding the efficacy of their application-specific prototypes without comparative evaluations. The visual representation of AR agents received the highest attention (15 papers), followed by behavior and traits (14 papers), display and interfaces (13 papers), physical-virtual interactivity (13 papers), and proxemics (9 papers). Research on the influences of display and interfaces received the highest ACC (4.9), followed by physical-virtual interactivity (4.89), visual representation (4.85) behavior and traits (4.47), and proxemics (3.14) (see Figure 3d).

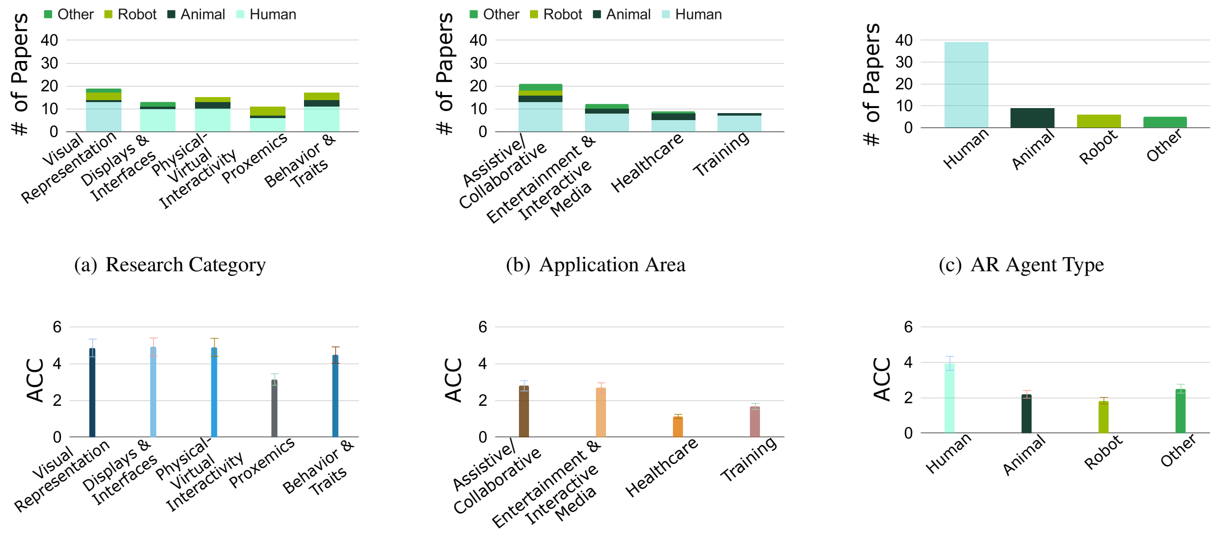
5. Detailed Reviews

In this section, we present detailed reviews of the collected papers based on the research categories that we defined in Section 3. In response to **RQ1**, we describe the current state of each specific research topic by providing the study settings and findings from the publications, while Section 6 covers trends and future directions.

5.1. Visual Representation

Out of our 50 papers, 15 investigated the effects of AR agents' visual representations, such as the presence of visual embodiment, different appearances, and visual qualities. Most papers researched how the presence of the AR agent's visual embodiment could influence the perception of the agent (9 papers). Five papers studied the AR agent's type, such as, humanoid appearances or non-human ones, such as robots and animals. Four papers focused on the size and proportion of the AR agent, and two covered the visual fidelity or realism of AR agents. Here, we present an in-depth review of some of these papers.

Regarding the impact of an AR agent's visual representation beyond the audio representation, Kim et al. studied the effects of an AR agent's embodiment visually appearing in the user's environment compared to disembodied voice agents in different scenarios—a personal assistant [KBH*18], a patient care assistant [KNL*19], and a collaborative decision supporter [KdMN*20]. All the studies in their work showed that the visual representation of the AR agent increased the perceived social presence with and social richness of the agent, and the participants in the personal and patient care assistant scenarios reported experiencing higher level of engagement in the interaction with the visual agents than the voice agents. Miller et al. [MJH*19] presented a series of studies related to the social influence of AR agents. One of the studies investigated social facilitation induced by an AR agent's visual presence using anagram tasks, resulting in participants performing the simple task better and the hard task worse when the AR agent was present than when performing the tasks alone. An AR agent's visual representation has been employed for improving the user experience in human-robot interactions. Dragone et al. [DHO07] prototyped a visual AR agent displayed on top of a moving robot as a social interface to communicate with the users, finding that the AR representation helped increase the perceived



(a) Research Category (b) Application Area (c) AR Agent Type

(d) Research Category (e) Application Area (f) AR Agent Type

Figure 3: *Number of papers (top row) and ACC (bottom row) of the reviewed papers plotted against the different (a & d) research categories, (b & e) application areas, and (c & f) AR agent types.*

reliability of the robot and the enjoyment in the interaction. Similarly, Haesler et al. [HKBW18] used a visual AR agent to represent an Amazon Echo system, showing that the AR agent's visual representation could help to increase the confidence in the system.

The type of an AR agent's appearance (e.g., human, robot, or animal) has been studied to see its effects on the user's behavior and perception of the agent. Li et al. [LAG*18] and Peters et al. [PLY*18] conducted user studies investigating the social distance between the participants when interacting with humanoid or robotic agents. They found that the humanoid agent could increase the level of perceived copresence with the human agent than the robot-type agent. Gushima et al. [GAN17] prototyped an AR agent with a jellyfish appearance that could provide daily information to the users as a social notification system, and compared with a human-type agent. While the users preferred the jellyfish for social media content, they wanted a lower-pitched human voice to hear other content, like the news. Multiple studies investigated the effects of agent size on human perception and design implications [WSR19, AKYT00, AM13] For instance, in a study by Wang et al. [WSR19], participants liked the miniature humanoid AR agent the most and disliked the full sized humanoid while also comparing with other voice-only and non-humanoid agents.

Visual realism is also an important factor in the AR agent's representation that could influence the user's perception. Mostajeran et al. [MSAN*20] explored the acceptability of virtual coaches for balance training for older adults. In their study, participants were shown four types of AR agents—realistic and cartoonish male/female avatars. They preferred the realistic male virtual coach over the rest. Reinhardt et al. [RHW20] studied how the different levels of realism in the embodied AR agent's visual representation could affect the user experience. In the study, the more realistic AR agents provided gestural communication cues, such as eye contact and gaze, while the other AR agents (i.e., invisible or wireframe appearance) had no social cues. The realistic AR agents were preferred over the invisible ones, but interestingly the invisible agents were less distracting to users, i.e., they were beneficial when the situation required visual attention as in multitask situations.

5.2. Displays and Interfaces

The papers in this section primarily study aspects related to the display modality and interfaces used to view and interact with the AR agents (13 papers total). Out of these display-focused papers, five of them involved system evaluations of prototype systems.

Of the papers that evaluated display modality aspects, twelve primarily investigated differences between users viewing AR agents on AR Displays compared to non-AR displays and platforms, such as physical prototypes [Sep03, GRH*14, WBBA12], or other display modalities [BKJ*19, ONP11, ZZH*18, DML*06, DMH*07, KSH*19]. Several interesting conclusions can be drawn from these papers, most notably that users sometimes behave differently in AR versions of the same content than they do in non-AR versions. For example, in the papers by Dow et al. users interact with AR agents in an interactive drama system [DML*06, DMH*07]. Their work found that users were less likely to haphazardly explore their environment or act in a socially unacceptable manner due to not wanting to break social norms. They also note that viewing content in AR modalities rather than non-AR modalities raises the users' expectations of what the system and AR agents are capable of. Gil et al. also investigated differences between AR and non-AR modalities through a study in which children were tasked to read aloud using an AR annotated book and a traditional book [GRH*14]. They found that children were more likely to actively participate and exhibit self-based perspectives toward the characters in the story when using the AR system compared to the non-AR.

Another topic in this category is the persistence of an AR agent's influence, after the user has taken off the HMD. Miller et al. [MJH*19] studied this concept by asking the participants to either take off their AR HMD or keep it on, and sit in one of two chairs, one of which occupied by an AR agent. They found that both participant groups chose the unoccupied chair more significantly in line with social norms.

Another topic is the effects of AR displays' field of view (FoV). Lee et al. investigated this effect in a study where users viewed an AR agent with either a regular HoloLens one, or one with a restricted visor that allowed the user to only see through the portion of the HMD where virtual content is rendered [LBHW18]. This visor reduced the users' FOV of their environment while eliminating disappearance issues that occur when AR agents are larger than the display's FoV. While they hypothesized that eliminating this disappearance issue would affect the users' perception of the AR agent, no significant effects were found. However, users' proxemics behavior were affected, such as slower walking speeds.

We found only one paper which somewhat evaluated UIs for interaction with AR agents. In this paper, by Scmeil and Broll, users could interact with an AR agent assistant either via voice commands or a mouse and cursor [SB07]. Although the two interfaces were not compared formally, user feedback suggested that speech recognition-based input "needs to be improved," but is "very intuitive" to use, while the mouse and cursor style input was also considered "rather feasible" by users.

5.3. Physical-Virtual Interactivity

We found 13 papers researching the AR agent's physical-virtual interactivity, covering four areas related to awareness of the physical environment (6 papers), visual coherence in the environment (4 papers), ability to control the environment (4 papers), and haptic feedback (3 papers)—some papers cover multiple sub-categories.

The research on the physical-virtual interactivity of AR agents often involves the agent's ability to be aware of and control the surrounding physical environment (i.e., human interlocutors or physical objects). Damian et al. [DKO*13] presented an AR agent that could recognize the user's motion/pose, specifically the hands positions, and provide feedback in time to guide certain postures in the given study tasks. Comparing with an AR agent that provides random feedback, the awareness-based feedback made the agent be perceived as more realistic and physically present in the shared space with the users. Kim et al. [Kim18, KSH*19] prototyped an AR agent that could be aware of peripheral events in an AR environment, where the real airflow from a physical fan could influence virtual paper and curtains nearby the agent. Their study showed that the physical-virtual airflow interaction and the AR agent's nonverbal awareness behavior, e.g., looking at the fan or trying to grab the fluttering virtual paper, could increase the perceived copresence with the agent. Kim et al. [KMB*17] further studied the impact of more explicit agent behavior exhibiting awareness of the environment. In the study, the AR agent verbally requested help from the participants to move an physical obstacle away, so that she could avoid implausible visual conflict with it, which resulted in positive responses of participants about the AR agent's physical awareness and social presence. Norouzi et al. [NKL*19] also showed positive results with a virtual dog that could be aware of the user's feet and behave accordingly, for example, the dog was falling over and whining when it was stepped over. These awareness behaviors of AR agents are normally visually coherent in the environment, for instance, visually plausible occlusions and compliance to the rules in the physical world avoiding physical-virtual conflict. Kim et al. [KBW17] studied the importance of visual coherence using an AR agent with ghost-like behaviors passing through physical obstacles. They found that such visual incoherence could significantly aggravate the AR agent's perceived physicality and animacy.

Regarding the ability to control the environment, Lee et al. [LNB*18, LNB*19] developed a tabletop gaming platform enabling an AR agent to move her physical token on the table while playing a board game with the users. In their study, they compared two conditions where the AR agent could move either a physical or a virtual token. They found that the AR agent's ability to control the physical one positively influenced the participants' sense of copresence with it and its perceived ability to move other real objects in the environment, such as small toys. Kim et al. [KBH*18] and Heasler et al. [HKBW18] employed "smart" objects for AR agents to control the physical world, for example, turn the floor lamp on/off through the the Internet of Things (IoT)-enabled light bulb. They found that such physical interactivity of the AR agent, together with appropriate locomotion, could increase the participants' confidence in the agent's task performance.

The perception of the AR agent's physical interactivity could be through indirect/direct haptics. As a direct way, Okumoto et al. [OZS12] and Sawada et al. [SJT11] presented a dataglove-based interaction with miniature cartoonish AR agents displayed on top of the hands. Different types of haptic feedback for the AR agent were devised, e.g., walking or slipping, and the preliminary evaluation showed that the haptic feedback could make the participants feel the agent's physical presence and encouraged more interactions with it. Lee et al. [LBHW18] explored indirect approaches by developing a vibrotactile platform that users could feel a humanoid AR agent's footsteps through a shared floor occupied by the agent and the user. They found that when comparing the AR agent in the haptic footstep feedback condition to those without it, participants subjectively perceived the agent as more realistic and physically copresent, while also adjusting their behavior, such as slowing down, indicating increased hesitance when sensing the footsteps.

5.4. Proxemics

The field of proxemics covers the study of space around and between humans, in particular considering interpersonal space, indicating the relative distances between people [Hal90], as well as their correlations with behavior, communication, and interaction. Nine out of our 50 papers studied proxemics, focusing on the spatial relationships between AR agents and users.

The earliest work we found in this area and the only work in the first decade is done by Anabuki et al. [AKYT00]. They introduced an anthropomorphic AR agent, Welbo, and through experiments, found that spatial factors could affect users' impressions of Welbo. For example, participants felt more comfortable when Welbo kept some distance and not floated over them. Research on the comfortable social distance between humans and AR agents was researched more frequently later. Aramaki and Murakami [AM13] reported 70cm based on their experiments using a 18cm cartoonish AR agent. While Peters et al. [PLY*18] reported 1.23m as the average comfortable distance for the four types of AR agents they experimented (male, female, small and full-sized robot) and pointed out that the small robot tended to induce a larger distance as people regarded it as being child-like. The different results may be due to the different interaction settings - in the former the agent was standing on the table, while in the latter the agent was placed on the ground and kept mutual gaze with participants. Interestingly, Bailenson et al. noted that people tended to keep a larger interpersonal distance from virtual agents with mutual gazes [BBBL03]. In recent example, Lang et al. [LLY19] proposed to position the agent by understanding the scene semantics. They reconstructed 3D models of the real world, detected key objects, and refined the position and orientation of the agent by optimizing a cost function.

Other examples studied the influences of an AR agent's behavior and spatial factors on participants' proxemics behaviors [ONP11, ODK*12, LAG*18]. Obaid et al. [ONP11] found that people talking to a more distant AR agent would speak louder and be more sensitive to spatial relationships in AR environments than VR environments. Besides direct interactions, Lee et al. [LAG*18] looked into a passing-by scenario. They studied people's different behaviors, such as clearance distances, walking speeds and head motions while passing by a virtual or real human that was standing idly, jumping regularly or walking back and forth. They observed that in some cases participants behaved differently with the AR agent compared to the real human, such as longer walking trajectories and slower speeds for the standing conditions. The authors suggested that this phenomenon might be due to virtual humans being perceived as less predictable in terms of following social norms. Besides AR agents with humanoid appearances, Norouzi et al. [NKL*19] investigated the influence of an AR dog on people's proxemics behavior with real human bystanders. They found that the AR dog's presence significantly affected participants' proxemics behaviors regardless of the bystander's awareness of the dog.

5.5. Behavior and Traits

Out of 50 papers, 14 studied the influence of AR agents' behavior and traits. Twelve papers varied agents' nonverbal behavior, such as facial expression, gaze, posture, and gestures. Only two papers studied the effects of contextual speech on the quality of human-AR agent interaction. Most papers (11 papers) the behavioral variations were intended to enhance the AR agent's sense of physicality (see Section 5.3), with a few examples (3 papers) where the influences of different behaviors and traits were the primary focus.

One paper that primarily focused on the development of an AR agent's behavior is by Randhavane et al. [RBK*19], aimed at creating a humanoid agent with a friendly demeanor. They developed a "friendliness" model for gait, gesture, and gaze, and utilized this model through an algorithm for generating friendly behaviors. Using this algorithm for an AR agent, they found that interacting with the friendly AR agent increased participants' sense of social and spatial presence compared to a baseline agent. Similarly, Li et al. [LAG*18] studied the influence of posture and facial expression of AR agents and their real counterparts, observing that open postures increased the participants' willingness to interact in all conditions. In this area, Obaid et al. [ODK*12] simulated culture-specific behaviors in a multi-agent interaction manifested through AR agents' interpersonal distance and gaze behavior.

In several examples, researchers studied the influence of augmenting AR agents with an illusion of physicality by manipulating their behavior, and/or utilizing external tools, such as haptic and IoT-enabled devices. In most cases, AR agents' nonverbal behaviors were varied, such as changes in hand gestures, gaze behavior, and head motion to indicate the AR agent's awareness of its physical environment [KMB*17, KBW17, KSH*19, Kim18, NKL*19, DKO*13, LBHW18]. A few examples, studied the influence of contextual speech on AR agents' perceived awareness of its environment [KMB*17, DKO*13]. Other works focused on the AR agent's physicality by synchronizing its behavior with devices providing haptic feedback, such as vibrations on the floor [LBHW18] or through a glove [OZS12, SJT11] to simulate footsteps or a sliding behavior. Another example of leveraging external mechanisms is the use IoT-enabled devices where researchers studied the influence of AR agents' nonverbal behavior during control of physical objects on the quality of interaction [KBH*18, HKBW18].

6. Emerging Trends and Future Directions

In this section, we present identified trends in the context of common roles where embodied AR agents were utilized or envisioned to address **RQ2**. We propose open research areas inspired by previous trends in other domains of augmented reality and robotics research in response to **RQ4**. Exploring the proposed areas does not necessarily depend on the quality of the state of the art technology as in many cases Wizard of Oz setups can be utilized.

[RQ2] AR Agents in Assistive/Collaborative Roles: In recent years, corresponding to increased commercial popularity of voice-based assistants such as Amazon Alexa or Google Home Assistant [LQG17], the notion of embodied agents has received increasing attention [NBB*19]. For example, AR HMDs have been used to provide a 3D body for such assistants, with results indicating benefits for assistive/collaborative roles [WSR19, RHW20, KBH*18, KNL*19, MSAN*20, KdMN*20]. In this area, an increasing presence of IoT-enabled devices has presented research opportunities for AR assistants capable of controlling various appliances through physically and contextually coherent behavior, with findings supporting the idea that such behaviors enhance a user's confidence in the AR assistants [KBH*18, HKBW18]. These findings, together with the anticipated increasing integration of IoT-enabled "smart" devices in everyday life [RS19] give rise to new research questions related to networked smart sensing and actuating modules, e.g., in smart home environments, as a mechanism for enhancing an AR agent's awareness and understanding of the physical environment.

[RQ2] AR Agents in Other Identified Application Areas: With respect to the application areas that arose during our literature survey (see Section 3), most papers focused on the use of AR agents in an assistive/collaborative role. Comparatively less research has been carried out in other application areas, such as entertainment and interactive media. This may be partly due to current limitations of AR HMD technologies, e.g., their ergonomics and lighting requirements [EKBW20], and their limited availability compared to the ubiquity of smartphones as an alternative platform for AR apps (e.g., Pokemon Go). In other application areas, such as healthcare and training, less research might be due to the cost and logistical difficulties associated with AR HMDs with more reliance on other mediums such as spatial augmented reality (SAR) or other displays [DHN*18, CWW*17, DHN*19]. However, with the increasing availability of inexpensive COTS AR HMDs such as the Microsoft HoloLens or Magic Leap One, we anticipate a steadily increasing range of applications that might benefit from AR agents in single and multi-user experiences. Through our literature survey, we are seeing an increase in the number of studies that evaluate the capabilities of AR HMDs, AR agents, and their effects on the users (see Section 4). This trend is likely to continue into the foreseeable future as newer generation HMDs with extended feature sets (e.g., embedded hand tracking or eye tracking) present opportunities to develop new knowledge about interactions with AR agents.

[RQ4] AR Agents as Companions: During our review, we noted a few examples that motivated or presented AR agents associated with companionship [CL18, NKL*19]. Previous research investigated the use of robots or virtual agents in other platforms (e.g., desktop-based) as companions or therapy partners with promising results [VRB*12,DTLL16,BHDB18,ŠBCH13]. With findings supporting the importance of long-term interactions for artificial pets and social robots [LLK15,LM12], we speculate that some limiting factors of current AR HMDs, such as limited availability, heavy weight, and small FoV might have affected the potential use of this technology for researching AR agents in companionship and therapeutic roles. However, with advances in technology and the growing availability of AR HMDs, we foresee new research opportunities for AR agents in this domain for reasons such as the potential for pervasive presence in our physical environment, their anticipated capacity for spatial and contextual understanding, and their flexibility in embodying different types and appearances. Such factors pose new research questions on the extent of their influence compared to other technological companions, as the technology itself evolves and becomes more readily available.

[RQ4] AR Agents and Multimodal Communication: As research on AR agents in HMD environments grows in different areas (see Section 4) where such agents could become embedded into our professional settings as well as our daily social lives, new questions arise with regards to how such agents should communicate, move, and behave such that they are compatible with other social entities. In particular, depending on the context of interaction in both AR and non-AR environments, we see an emerging trend in the way that voice-based communication is enhanced with other modalities that can complement speech interactions [KdMN*20, WSR19, SYM*18], although we did not identify examples solely relying on nonverbal communication, certain real-life circumstances where speech is not a convenient communication mechanism, present new research questions regarding the effectiveness of AR agents' nonverbal behavior communication. For instance, in environments with high ambient noise, users and AR agents may rely on pointing or gazing towards objects for communication, and a plethora of other possible social signals. We further observed an increasing number of works related to proxemics with AR agents in social spaces, emphasizing that such agents need to move through social spaces in a natural way, which includes maintaining an acceptable social distance. We believe that more proxemics research is necessary to understand the spatial relationship between users and AR agents in different social situations.

[RQ4] AR Agents and Influence of Personality and Empathy: In line with previous non-AR research focused on agents' personalities and emotions, we identified a few examples where the primary research focus was to understand the impact of such aspects, like friendliness and openness. [RBK*19, ODK*12, LAG*18]. As past research suggests that interactions with AR agents can have different influences on users on aspects such as social presence, and involvement [KSH*19,DMH*07,ZZH*18] new research questions arise as to the extent of AR agents' personality influence in different interaction contexts. Also, borrowing from previous literature in AR/VR human-human collaboration studying ways of transferring users' emotions or perspectives to promote empathy [MKSB16, PDE*17], and the recent examples identified in our work of human-AR agent collaborations [WSR19, KdMN*20], we predict new research opportunities in realizing AR agent's capable of empathy and perspective-taking by understanding a user's facial expression, tone, or situational context.

7. Conclusion

In this paper, we presented a systematic literature review of previous research on interactive embodied AR agents presented on HMDs. We provided detailed reviews of 50 related papers covering the years from 2000 to 2020. In particular, we discussed papers that aimed at improving our understanding of AR agents or their utilization in application domains. We identified common research and application areas of AR agents, presented research trends and gaps, and shared insights on future directions, which may help to structure and foster future research in this emerging field.

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References

[AGTV18] ARUANNO B., GARZOTTO F., TORELLI E., VONA F.: Hololearn: Wearable mixed reality for people with neurodevelopmental disorders (ndd). In *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility* (2018), pp. 40–51. 4

[AKYT00] ANABUKI M., KAKUTA H., YAMAMOTO H., TAMURA H.: Welbo: An embodied conversational agent living in mixed reality space. In *CHI'00 Extended Abstracts on Human Factors in Computing Systems* (2000), pp. 10–11. 5, 6

[AM13] ARAMAKI R., MURAKAMI M.: Investigating appropriate spatial relationship between user and ar character agent for communication using ar woz system. In *Proceedings of the 15th ACM on International Conference on Multimodal Interaction* (2013), pp. 397–404. 5, 7

[BBBL03] BAILENSON J. N., BLASCOVICH J., BEALL A. C., LOOMIS J. M.: Interpersonal distance in immersive virtual environments. *Personality and Social Psychology Bulletin 29*, 7 (2003), 819–833. 7

[BHDB18] BETHEL C. L., HENKEL Z., DARROW S., BAUGUS K.: Therabot-an adaptive therapeutic support robot. In *IEEE World Symposium on Digital Intelligence for Systems and Machines (DISA)* (2018), pp. 23–30. 8

[BKJ*19] BÖNSCH A., KIES A., JÖRLING M., PALUCH S., KUHLEN T. W.: An empirical lab study investigating if higher levels of immersion increase the willingness to donate. In *2019 IEEE Virtual Humans and Crowds for Immersive Environments (VHCIE)* (2019), pp. 1–4. 5

[CGMB20] CARROZZINO M. A., GALDIERI R., MACHIDON O. M., BERGAMASCO M.: Do virtual humans dream of digital sheep? *IEEE Computer Graphics and Applications 40*, 4 (2020), 71–83. 1

[CL18] CHAO T.-Y., LIN S.-F.: A mixed reality system to improve walking experience. In *Proceedings of the IEEE International Conference on System Science and Engineering (ICSSE)* (2018), pp. 1–4. 8

[CWW*17] CORDAR A., WENDLING A., WHITE C., LAMPOTANG S., LOK B.: Repeat after me: Using mixed reality humans to influence best communication practices. In *Proceedings of the IEEE Virtual Reality* (2017), pp. 148–156. 8

[DAB*14] DEVAULT D., ARTSTEIN R., BENN G., DEY T., FAST E., GAINER A., GEORGILA K., GRATCH J., HARTHOLT A., LHOMMET M., ET AL.: Simsensei kiosk: A virtual human interviewer for healthcare decision support. In *Proceedings of the International Conference on Autonomous Agents and Multi-Agent Systems* (2014), pp. 1061–1068. 1

[DBLS18] DEY A., BILLINGHURST M., LINDEMAN R. W., SWAN J.: A systematic review of 10 years of augmented reality usability studies: 2005 to 2014. *Frontiers in Robotics and AI 5* (2018), 37. 3

[DHN*18] DAHER S., HOCHREITER J., NOROUZI N., GONZALEZ L., BRUDER G., WELCH G.: Physical-virtual agents for healthcare simulation. In *Proceedings of the ACM International Conference on Intelligent Virtual Agents* (2018), pp. 99–106. 1, 8

[DHN*19] DAHER S., HOCHREITER J., NOROUZI N., SCHUBERT R., BRUDER G., GONZALEZ L., ANDERSON M., DIAZ D., CENDAN J., WELCH G.: [POSTER] Matching vs. Non-Matching Visuals and Shape for Embodied Virtual Healthcare Agents. In *IEEE Virtual Reality* (2019). 8

[DHO07] DRAGONE M., HOLZ T., O'HARE G. M.: Using mixed reality agents as social interfaces for robots. In *Proceedings of the 16th IEEE International Symposium on Robot and Human Interactive Communication* (2007), pp. 1161–1166. 4

[Dig19] DIGITAL DOMAIN: Virtual Humans. digitaldomain.com/digital-humans/, September 2019. 1

[DKO*13] DAMIAN I., KISTLER F., OBAID M., BUHLING R., BILLINGHURST M., ANDRE E.: Motion capturing empowered interaction with a virtual agent in an Augmented Reality environment. In *Extended Abstracts of the IEEE International Symposium on Mixed and Augmented Reality* (2013), pp. 1–6. 6, 7

[DMH*07] DOW S., MEHTA M., HARMON E., MACINTYRE B., MATEAS M.: Presence and engagement in an interactive drama. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2007), p. 1475–1484. 5, 8

[DML*06] DOW S., MEHTA M., LAUSIER A., MACINTYRE B., MATEAS M.: Initial lessons from ar façade, an interactive augmented reality drama. In *Proceedings of the ACM SIGCHI International Conference on Advances in Computer Entertainment Technology* (2006). 5

[DTLL16] DEMIRIS G., THOMPSON H. J., LAZAR A., LIN S.-Y.: Evaluation of a digital companion for older adults with mild cognitive impairment. In *AMIA Annual Symposium Proceedings* (2016), vol. 2016, American Medical Informatics Association, p. 496. 8

[EKBW20] ERICKSON A., KIM K., BRUDER G., WELCH G.: Exploring the Limitations of Environment Lighting on Optical See-Through Head-Mounted Displays. In *Proceedings of the ACM Symposium on Spatial User Interaction* (2020). 8

[GAN17] GUSHIMA K., AKASAKI H., NAKAJIMA T.: Ambient bot: delivering daily casual information through eye contact with an intimate virtual creature. In *Proceedings of the 21st International Academic Mindtrek Conference* (2017), pp. 231–234. 5

[GRH*14] GIL K., RHIM J., HA T., DOH Y. Y., WOO W.: AR Petite Theater: Augmented Reality Storybook for Supporting Children's Empathy Behavior. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality - Media, Art, Social Science, Humanities and Design (ISMAR-MASH'D)* (2014), pp. 13–20. 5

[Hal90] HALL E. T.: *The Hidden Dimension*. Anchor Books, 1990. 6

[HCO*11] HOLZ T., CAMPBELL A. G., O'HARE G. M., STAFFORD J. W., MARTIN A., DRAGONE M.: MiRA—Mixed Reality Agents. *International Journal of Human-Computer Studies 69*, 4 (2011), 251–268. 2

[HKBW18] HAESLER S., KIM K., BRUDER G., WELCH G.: Seeing is believing: Improving the perceived trust in visually embodied alexa in augmented reality. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (2018), pp. 204–205. 5, 6, 7

[JAM*14] JOHNSEN K., AHN S. J., MOORE J., BROWN S., ROBERTSON T. P., MARABLE A., BASU A.: Mixed reality virtual pets to reduce childhood obesity. *IEEE Transactions on Visualization and Computer Graphics 20*, 4 (2014), 523–530. 1

[KBB*18] KIM K., BILLINGHURST M., BRUDER G., DUH H. B.-L., WELCH G. F.: Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008–2017). *IEEE Transactions on Visualization and Computer Graphics 24*, 11 (2018), 2947–2962. 1, 3

[KBH*18] KIM K., BOELLING L., HAESLER S., BAILENSON J. N., BRUDER G., WELCH G. F.: Does a Digital Assistant Need a Body? The Influence of Visual Embodiment and Social Behavior on the Perception of Intelligent Virtual Agents in AR. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality* (2018), pp. 105–114. 4, 6, 7

[KBW17] KIM K., BRUDER G., WELCH G.: Exploring the Effects of Observed Physicality Conflicts on Real–Virtual Human Interaction in Augmented Reality. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* (2017), pp. 31:1–7. 6, 7

[KdMN*20] KIM K., DE MELO C. M., NOROUZI N., BRUDER G., WELCH G. F.: Reducing Task Load with an Embodied Intelligent Virtual Assistant for Improved Performance in Collaborative Decision Making. In *Proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces* (2020), pp. 529–538. 4, 7, 8

[Kim18] KIM K.: Improving Social Presence with a Virtual Human via Multimodal Physical–Virtual Interactivity in AR. In *Extended Abstracts of the ACM CHI Conference on Human Factors in Computing Systems (Student Research Competition)* (2018), pp. SRC09:1–6. 6, 7

[KMB*17] KIM K., MALONEY D., BRUDER G., BAILENSON J. N., WELCH G. F.: The effects of virtual human's spatial and behavioral coherence with physical objects on social presence in AR. *Computer Animation and Virtual Worlds 28*, 3-4 (2017), e1771. 6, 7

[KNL*19] Kim K., Norouzi N., Losekamp T., Bruder G., Anderson M., Welch G.: Effects of patient care assistant embodiment and computer mediation on user experience. In *Proceedings of the IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)* (2019), IEEE, pp. 17–24. 4, 7

[KSH*19] Kim K., Schubert R., Hochreiter J., Bruder G., Welch G.: Blowing in the wind: Increasing social presence with a virtual human via environmental airflow interaction in mixed reality. *Computers & Graphics 83* (Oct 2019), 23–32. 5, 6, 7, 8

[LAG*18] Li C., Androulakaki T., Gao A. Y., Yang F., Saikia H., Peters C., Skantze G.: Effects of posture and embodiment on social distance in human-agent interaction in mixed reality. In *Proceedings of the 18th ACM International Conference on Intelligent Virtual Agents* (2018), pp. 191–196. 5, 7, 8

[LAT*09] Liberati A., Altman D. G., Tetzlaff J., Mulrow C., Gøtzsche P. C., Ioannidis J. P., Clarke M., Devereaux P. J., Kleijnen J., Moher D.: The prisma statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Annals of Internal Medicine 151*, 4 (2009), W–65. 2

[LBHW18] Lee M., Bruder G., Höllerer T., Welch G.: Effects of Unaugmented Periphery and Vibrotactile Feedback on Proxemics with Virtual Humans in AR. *IEEE Transactions on Visualization and Computer Graphics 24*, 4 (2018), 1525–1534. 6, 7

[LGH*17] Livoreil B., Glanville J., Haddaway N. R., Bayliss H., Bethel A., de Lachapelle F. F., Robalino S., Savilaakso S., Zhou W., Petrokofsky G., et al.: Systematic searching for environmental evidence using multiple tools and sources. *Environmental Evidence 6*, 1 (2017), 1–14. 2

[LLK15] Luh D.-B., Li E. C., Kao Y.-J.: The development of a companionship scale for artificial pets. *Interacting with Computers 27*, 2 (2015), 189–201. 8

[LLY19] Lang Y., Liang W., Yu L.-F.: Virtual Agent Positioning Driven by Scene Semantics in Mixed Reality. In *Proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces* (2019), pp. 767–775. 7

[LM12] Lakatos G., Miklósi Á.: How can the ethological study of dog-human companionship inform social robotics? In *Crossing Boundaries*. Brill, 2012, pp. 187–208. 8

[LNB*18] Lee M., Norouzi N., Bruder G., Wisniewski P. J., Welch G. F.: The Physical-Virtual Table: Exploring the Effects of a Virtual Human's Physical Influence on Social Interaction. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology* (2018), pp. 1–11. 6

[LNB*19] Lee M., Norouzi N., Bruder G., Wisniewski P. J., Welch G. F.: Mixed Reality Tabletop Gameplay: Social Interaction with a Virtual Human Capable of Physical Influence. *IEEE Transactions on Visualization and Computer Graphics 24*, 8 (2019), 1–12. 6

[LQG17] López G., Quesada L., Guerrero L. A.: Alexa vs. siri vs. cortana vs. google assistant: a comparison of speech-based natural user interfaces. In *Proceedings of the International Conference on Applied Human Factors and Ergonomics* (2017), Springer, pp. 241–250. 7

[LRK*19] Lopatovska I., Rink K., Knight I., Raines K., Cosenza K., Williams H., Sorsche P., Hirsch D., Li Q., Martinez A.: Talk to me: Exploring user interactions with the Amazon Alexa. *Journal of Librarianship and Information Science 51*, 4 (2019), 984–997. 3

[Mag19] Magic Leap: I Am Mica. https://www.magicleap.com/en-us/news/op-ed/i-am-mica, January 2019. 1

[MDC18] Machidon O. M., Duguleana M., Carrozzino M.: Virtual humans in cultural heritage ict applications: A review. *Journal of Cultural Heritage 33* (2018), 249–260. 1

[Mic18] Microsoft: Fragments. https://docs.microsoft.com/en-us/windows/mixed-reality/case-study-creating-an-immersive-experience-in-fragments, March 2018. 1

[MJH*19] Miller M. R., Jun H., Herrera F., Yu Villa J., Welch G., Bailenson J. N.: Social interaction in augmented reality. *PLOS ONE 14*, 5 (2019), e0216290. 4, 6

[MKSB16] Masai K., Kunze K., Sugimoto M., Billinghurst M.: Empathy glasses. In *Proceedings of the ACM CHI Conference Extended Abstracts on Human Factors in Computing Systems* (2016), pp. 1257–1263. 8

[MS09] Miller M. K., Summers A.: A content analysis of the evolution of video game characters as represented in video game magazines. *Journal of Media Psychology 14*, 3 (2009). 1

[MSAN*20] Mostajeran F., Steinicke F., Ariza Nunez O. J., Gatsios D., Fotiadis D.: Augmented Reality for Older Adults: Exploring Acceptability of Virtual Coaches for Home-based Balance Training in an Aging Population. In *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems* (2020), pp. 1–12. 5, 7

[NBB*19] Norouzi N., Bruder G., Belna B., Mutter S., Turgut D., Welch G.: A systematic review of the convergence of augmented reality, intelligent virtual agents, and the internet of things. In *Artificial Intelligence in IoT*. Springer, 2019, p. 37. 1, 2, 7

[NKH*18] Norouzi N., Kim K., Hochreiter J., Lee M., Daher S., Bruder G., Welch G.: A Systematic Survey of 15 Years of User Studies Published in the Intelligent Virtual Agents Conference. In *Proceedings of the 18th ACM International Conference on Intelligent Virtual Agents* (2018), pp. 17–22. 1, 3

[NKL*19] Norouzi N., Kim K., Lee M., Schubert R., Erickson A., Bailenson J., Bruder G., Welch G.: Walking Your Virtual Dog: Analysis of Awareness and Proxemics with Simulated Support Animals in Augmented Reality. In *Proceedings of IEEE International Symposium on Mixed and Augmented Reality* (2019), pp. 253–264. 6, 7, 8

[OBW18] Oh C. S., Bailenson J. N., Welch G. F.: A systematic review of social presence: Definition, antecedents, and implications. *Frontiers in Robotics and AI 5*, 114 (2018). 3

[ODK*12] Obaid M., Damian I., Kistler F., Endrass B., Wagner J., André E.: Cultural behaviors of virtual agents in an augmented reality environment. In *Proceedings of the International Conference on Intelligent Virtual Agents* (2012), Springer, pp. 412–418. 7, 8

[ONP11] Obaid M., Niewiadomski R., Pelachaud C.: Perception of Spatial Relations and of Coexistence with Virtual Agents. In *Proceedings of the International Conference on Intelligent Virtual Agents*. 2011, pp. 363–369. 5, 7

[OZS12] Okumoto S., Zhao F., Sawada H.: Tactoglove presenting tactile sensations for intuitive gestural interaction. In *Proceedings of the IEEE International Symposium on Industrial Electronics* (2012), pp. 1680–1685. 6, 7

[PDE*17] Piumsomboon T., Day A., Ens B., Lee Y., Lee G., Billinghurst M.: Exploring enhancements for remote mixed reality collaboration. In *SIGGRAPH Asia 2017 Mobile Graphics & Interactive Applications*. 2017, pp. 1–5. 8

[PLY*18] Peters C., Li C., Yang F., Avramova V., Skantze G.: Investigating social distances between humans, virtual humans and virtual robots in mixed reality. In *Proceedings of the 17th International Conference on Autonomous Agents and Multi-Agent Systems* (2018), pp. 2247–2249. 5, 7

[PTS*17] Purington A., Taft J. G., Sannon S., Bazarova N. N., Taylor S. H.: "Alexa is my new BFF" Social Roles, User Satisfaction, and Personification of the Amazon Echo. In *Proceedings of the ACM CHI Conference Extended Abstracts on Human Factors in Computing Systems* (2017), pp. 2853–2859. 3

[RBK*19] Randhavane T., Bera A., Kapsaskis K., Gray K., Manocha D.: FVA: Modeling perceived friendliness of virtual agents using movement characteristics. *IEEE Transactions on Visualization and Computer Graphics 25*, 11 (2019), 3135–3145. 7, 8

[RHW20] Reinhardt J., Hillen L., Wolf K.: Embedding Conversational Agents into AR: Invisible or with a Realistic Human Body? In

Proceedings of the 14th International Conference on Tangible, Embedded, and Embodied Interaction (2020), pp. 299–310. 5, 7

[RS19] RAYES A., SALAM S.: Internet of Things (IoT) Overview. In *Internet of Things From Hype to Reality*. Springer, 2019, pp. 1–35. 7

[SB07] SCHMEIL A., BROLL W.: MARA - A Mobile Augmented Reality-Based Virtual Assistant. In *Proceedings of the IEEE Virtual Reality Conference* (2007), pp. 267–270. 6

[ŠBCH13] ŠABANOVIĆ S., BENNETT C. C., CHANG W.-L., HUBER L.: PARO robot affects diverse interaction modalities in group sensory therapy for older adults with dementia. In *Proceedings of the 13th IEEE International Conference on Rehabilitation Robotics (ICORR)* (2013), pp. 1–6. 8

[Sep03] SEPHTON T.: Teaching agents for wearable augmented reality systems. In *Proceedings of the 7th IEEE International Symposium on Wearable Computers* (2003), pp. 250–250. 5

[SJT11] SAWADA H., JIANG C., TAKASE H.: TactoGlove: Displaying Tactile Sensations in Tacto-gestural Interaction. In *Proceedings of the IEEE International Conference on Biometrics and Kansei Engineering* (2011), pp. 216–221. 6, 7

[SW18] SIAU K., WANG W.: Building trust in artificial intelligence, machine learning, and robotics. *Cutter Business Technology Journal 31*, 2 (2018), 47–53. 4

[SYM*18] SHI Y., YAN X., MA X., LOU Y., CAO N.: Designing emotional expressions of conversational states for voice assistants: Modality and engagement. In *Extended Abstracts of the ACM CHI Conference on Human Factors in Computing Systems* (2018), pp. 1–6. 8

[VRB*12] VARDOULAKIS L. P., RING L., BARRY B., SIDNER C. L., BICKMORE T.: Designing relational agents as long term social companions for older adults. In *Proceedings of the International Conference on Intelligent Virtual Agents* (2012), pp. 289–302. 8

[WBBA12] WRZESIEN M., BURKHARDT J.-M., BOTELLA C., ALCAÑIZ M.: Evaluation of the quality of collaboration between the client and the therapist in phobia treatments. *Interacting with Computers 24*, 6 (2012), 461–471. 5

[WBSS19] WELCH G., BRUDER G., SQUIRE P., SCHUBERT R.: *Anticipating Widespread Augmented Reality: Insights from the 2018 AR Visioning Workshop*. Tech. rep., University of Central Florida and Office of Naval Research, August 6 2019. 1

[WSR19] WANG I., SMITH J., RUIZ J.: Exploring virtual agents for augmented reality. In *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems* (2019), pp. 1–12. 4, 5, 7, 8

[ZZH*18] ZIELKE M. A., ZAKHIDOV D., HARDEE G. M., PRADEEP J., EVANS L., LODHI Z., ZIMMER K., WARD E.: Exploring medical cyberlearning for work at the human/technology frontier with the mixed-reality emotive virtual human system platform. In *Proceedings of the 6th IEEE International Conference on Serious Games and Applications for Health* (2018), pp. 1–8. 5, 8