The Physical-Virtual Table: Exploring the Effects of a Virtual Human's Physical Influence on Social Interaction

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ABSTRACT

In this paper, we investigate the effects of the physical influence of a virtual human (VH) in the context of face-to-face interaction in augmented reality (AR). In our study, participants played a tabletop game with a VH, in which each player takes a turn and moves their own token along the designated spots on the shared table. We compared two conditions as follows: the VH in the *virtual* condition moves a virtual token that can only be seen through AR glasses, while the VH in the *physical* condition moves a physical token as the participants do; therefore the VH's token can be seen even in the periphery of the AR glasses. For the *physical* condition, we designed an actuator system underneath the table. The actuator moves a magnet under the table which then moves the VH's physical token over the surface of the table. Our results indicate that participants felt higher co-presence with the VH in the *physical* condition, and participants assessed the VH as a more physical entity compared to the VH in the *virtual* condition. We further observed transference effects when participants attributed the VH's ability to move physical objects to other elements in the real world. Also, the VH's physical influence improved participants' overall experience with the VH. We discuss potential explanations for the findings and implications for future shared AR tabletop setups.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *Empirical studies in HCI*;

KEYWORDS

Augmented reality, virtual humans, mediated physicality

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1 INTRODUCTION

Augmented reality (AR) technologies have seen major advances over the last years with developments such as the Microsoft HoloLens and generally less expensive and more usable displays, sensors, and user interfaces [22]. While not there yet, it seems reasonable to assume that AR displays will become a common sight for home cinema, gaming, and related experiences over the next decade. In particular in peoples' homes, AR technologies can have a strong impact on how we interact with each other, e.g., using AR telepresence [37], and with virtual humans (VHs), such as embodied forms of intelligent virtual agents [23]. The advent of voice-controlled agents over the last years and their embodied AR counterparts have shown the potential of such agents to act as social entities in our daily life [38]. Such VHs can take on a plethora of roles that are typically taken by real humans in our daily lives, such as assistants, companions, supporters, or adversaries, e.g., when playing a tabletop game alone or in a group at home.

However, when interacting with a VH that is presented via optical see-through glasses such as the HoloLens, the challenge remains that the virtual content is not able to exert a direct influence over the physical entities in the room. This can have a negative effect on users' sense of *co-presence*, which is defined as "the degree to which one believes that he or she is in the presence of, and dynamically interacting with, other veritable human beings" [6–8]. Harms and Biocca described co-presence as one of several dimensions that make up *social presence*, i.e., one's sense of being socially connected with the other [16].

In this paper, we present a technical approach to realize physical-virtual interactivity in AR in the scope of a tabletop environment, and we present an example application and user study designed around a tabletop gaming experience between a real and a virtual human. The study involved two conditions in which the VH either exerted influence over *physical* or *virtual* tokens on the tabletop surface. With subjective and behavioral measures, we show benefits of the physical condition on the participants' sense of co-presence as well as their sense that the VH is a physical entity.

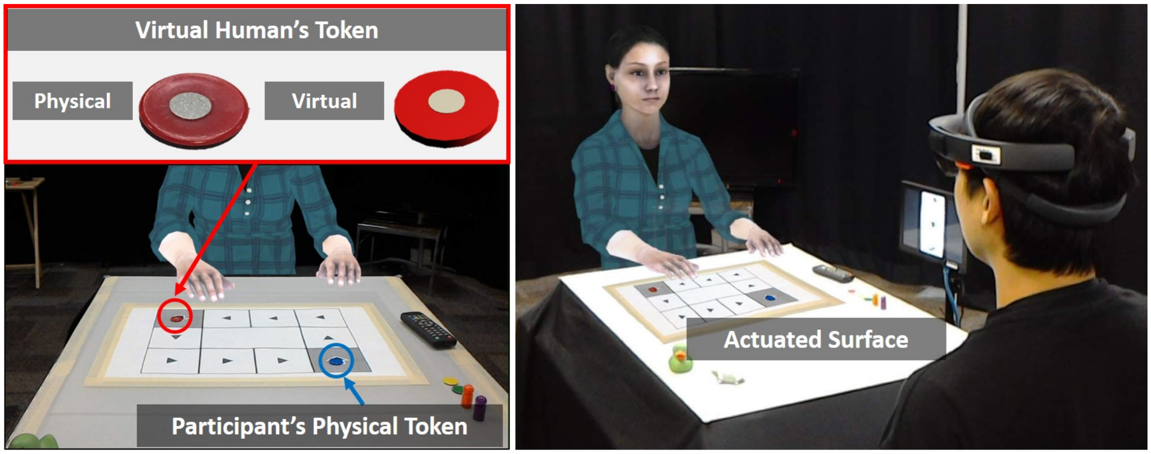


Figure 1: Illustration of the augmented reality game mechanics with virtual or physical game tokens on the left. The image on the right side shows the tabletop gaming surface with the magnetic actuator system underneath, which gives the illusion of the virtual human being able to touch and move physical objects over the surface.

This paper is structured as follows. Section 2 presents related work in the scope of VHs and physical-virtual interactivity. Section 3 describes the apparatus and tabletop setup that we developed to give the virtual content control over the movement of physical objects on a tabletop surface. Section 4 describes the human-subject study in which we investigate the benefits and drawbacks of such an influence. Section 5 presents the results which are discussed in Section 6. Section 7 concludes the paper and discusses future work.

2 RELATED WORK

In this section we resume related work on VHs in AR and their interaction with physical entities in the real environment.

2.1 Virtual Humans in AR

The term *virtual humans* in general refers to human-like entities comprised of a computer graphics and/or physical body. They can appear in a virtual environment or can share a physical space with real humans. Traditionally virtual humans are referred to as *avatars* or *agents* depending on the entity controlling them, where avatars are controlled by humans, while agents are controlled by computer programs [14]. Various application fields employ and draw benefits from VHs (see [34]). For example, Hoque et al. [19] developed a system for users to train their social skills, e.g., job interview skills, with VHs that could give personalized feedback. Because of the resemblance of VHs' appearance and shape with humans, people naturally distinguish them from non-human objects and often treat them in a similar way as real humans [2, 4, 33]. The phenomenon that people treat VHs as if they were real humans is often leveraged in training simulations, where they assume the roles of instructors or training partners that may not always be available.

Social presence and co-presence are commonly used constructs to measure users' perception of VHs. They are generalizable factors among many other simulation-dependent factors in assessing the effectiveness of training simulations that employ VHs. While many interpretations of the terms social presence and co-presence have been proposed (see [11]), Goffman et al. [15] indicated that co-presence exists when people feel that they are able to perceive others and that others are able to perceive them. Harm and Biocca [16] defined social presence as "one's sense of being socially connected with the other" and "one's sense of the other person's presence."

Researchers have investigated traits of VHs, e.g., appearance, shape, realistic gestures, to increase users' sense of social and co-presence. However, a relatively small amount of research has attempted to bring realistic three-dimensional VHs in users' physical environment in AR, compared to the majority of research performed in Virtual Reality (VR). Increasing convergence of AR and Robotics in different areas such as using AR as a social interface for a robot [12], robot path planning [3], or implementing a VH's autonomous behavior such as eye and head motion [21] through the advances of the same topic in the field of robotics [10, 35, 40], can provide a turning point in AR research. Meanwhile, efforts to make a social robot, e.g., for a human companion, has been steadily made in the robotics community [9], but they faced Uncanny Valley related challenges due to the complexity of representing realistic human facial expression as well as subtle body gestures [39]. Convergence of AR and robotics, i.e., the realistic 3D graphics of AR and the physical presence of robots, in this regard, might be mutually beneficial for both VHs in AR and social robots [18].

When VHs are brought into users' real space, two main approaches exist: (i) They can be partially or entirely projected onto physical objects that look like a human body, or (ii) they can be overlaid onto a user's view using AR technology. For example, Kotranza et al. [25] proposed a mannequin-based embodied agent, a virtual patient, that supports touch interaction with medical trainees. Similarly, Lincoln et al. [32] prototyped a robot-based embodied virtual human. They projected a human face onto an actuated robotic head which could convey non-verbal social behavior, such as gaze direction, as well as verbal communication. Obaid et al. [36] used video see-through AR glasses to augment the VH in a user's view in their study evaluating the relationship between the users' physiological responses and VHs' cultural behaviors.

However, there are perceptual issues one should consider when using AR glasses to overlay VHs in the users' view (see [26]). For instance, Lee et al. [28] showed that the small augmented field of view of the current-state optical see-through AR glasses can affect users' proxemic behavior in the presence of VHs. Also, Kim et al. [24] indicated that VHs' conflicting physical behavior with real objects, e.g., passing through them, could reduce users' sense of co-presence with the VH.

2.2 Physical-Virtual Interactivity

Bridging the gap between the physical world and virtual worlds has been of increasing interest in recent years. For instance, Sra et al. [43] introduced a method to create a walkable area in a virtual environment that is based on the space in the real world. Similarly, Simeone et al. [42] proposed a *substitutional reality* where the physical world is substituted with virtual counterparts, and showed a relation between the level of mismatch and the user experience in such an environment. Regarding the opposite direction, from virtual to real, researchers have proposed methods utilizing mobile robots and actuators. He et al. [17] demonstrated three different mapping mechanisms between physical and virtual objects in such scenarios. Kasahara et al. [20] proposed "exTouch", a touchscreen-based interaction method, to allow users to manipulate actuated physical object through AR. Joshua et al. [31] used networked actuators to bring virtual events into the physical world in their *cross reality* implementation.

Unlike VR, however, in augmented/mixed reality, virtual content is overlaid onto or mixed with the real world, creating a unified world. In such cases, the means by which virtual entities interact with the physical environment can affect users' perception. For example, Kim et al. [24] demonstrated that users rated the sense of social presence higher with a VH that exhibited awareness of the physical space, compared to one that did not in AR. This finding is comparable to the results of Bailenson et al. [4], in which a VH that exhibited awareness of the user in an immersive virtual environment received higher social presence and induced more realistic gaze and proxemic behavior with the participant.

Similarly, users had higher co-presence with a VH that could affect their physical space. Lee et al. [29] showed that participants rated co-presence higher with a VH when it could affect their physical space through a shared physical-virtual table in a mixed reality environment. They used an actuated wobbly table to establish such physical-virtual interactivity. Later, Lee et al. [28] also showed that subtle tactile vibrations of a VH's footsteps could induce higher co-presence with the VH in AR.

We are entering an era where VHs can be given more and more control over physical objects at our homes and in public spaces. With the Internet of Things (IoT), common devices in our daily lives are connected to computer systems that enable them to be accessed by voice-controlled agents, such as Amazon Alexa, providing an intuitive and natural interface to interact with them [38]. For instance, Kim et al. [23] investigated IoT devices as a VH's physical influence channel and compared the effects of embodied voice-controlled agents and their behavior on the user experience as well as social presence. They found that exhibiting plausible behavior, e.g., walking over to an IoT lamp and pretending to touch a light switch to turn it on, similar to what real humans would do, induced significantly higher social presence with the agent than voice-only interaction.

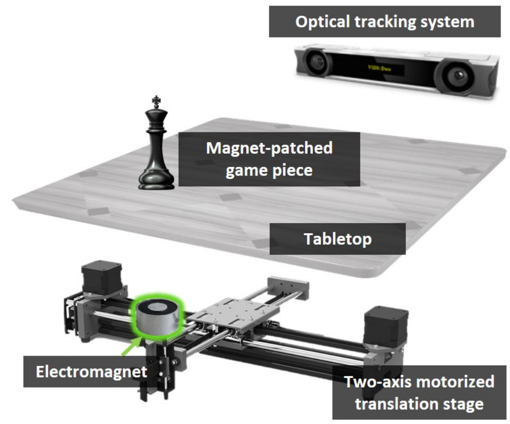


Figure 2: Apparatus: Tracked magnetically actuated game pieces on a tabletop surface realized through a motorized translation stage hidden from view underneath the surface.

In addition to those IoT devices, some tangible interfaces seem promising candidates for realizing physical-virtual interactivity for VHs. For example, Follmer et al. [13] developed a shape-changing surface with a grid of linear actuators and demonstrated various interaction techniques using the surface. Leithinger et al. [30] later used the shape-changing surface to allow two remote users to interact physically through the surface. The actuated surface in this paper is further inspired by the work by Lee et al. [27]. Though they did not consider AR or VHs, they presented an approach based on an electromagnet with a three-dimensional actuated stage to levitate a ball-shape permanent magnet in mid-air.

3 APPARATUS

This section describes the tabletop setup with the magnetic actuator system underneath the surface that we developed for use with a virtual human presented in AR (see Figure 1).

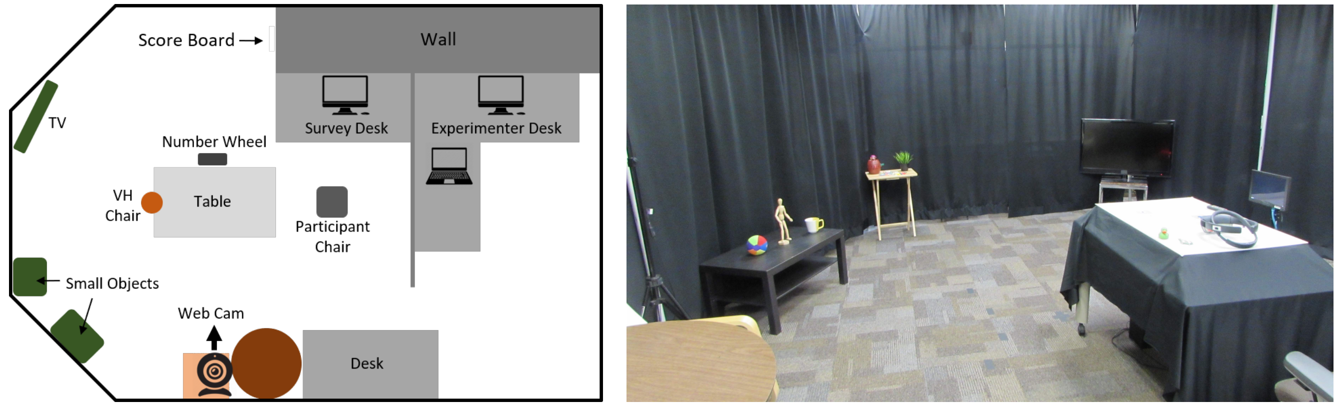
3.1 Magnetic Actuator Surface

We designed an apparatus that can extend the ability of VHs in AR to move physical objects on a surface (see Figure 2).

The apparatus comprises the four main components:

- A magnet that can attract magnet- or metal-patched physical objects on the surface of the table.
- A two-axis motorized *translation stage* that can move the magnet parallel to the surface of the tabletop.
- A tracking system that tracks the positions of physical objects on the table and sends the data to AR glasses to register virtual content accordingly.
- A tabletop that covers the translation stage and hides it from the user's view.

We used an EleksDraw Computer Numerical Control (CNC) machine for the two-axis motorized translation stage and mounted a magnet to the mobile part of the CNC machine at the tip where usually a drill or laser is attached. The working range of the translation stage is 280 mm × 200 mm, and the maximum speed is 83 mm/s.



(a) (b)

Figure 3: Experimental setup: (a) Illustration of the experimental space with the tabletop setup and other furniture and equipment, and (b) photo of the room with the tabletop gaming setup.

We used an ease in/out velocity curve for a natural movement of the token; the average speed of the token was 50 mm/s. We compared different electromagnets and permanent magnets, and we decided to use a robust permanent magnet (a neodymium magnet) for the study presented in this paper due to trade-offs between its magnetic force, the weight of the physical object on the surface, and the thickness of the surface.

We used an OptiTrack Duo optical tracking system to track the position of the physical objects on the surface. We mounted the cameras on the ceiling of the experimental space, looking down at the tabletop surface. As the OptiTrack system requires retroreflective infrared (IR) markers to track the position of objects, we attached small markers to the corners of the tabletop and to the game tokens.

We decided to use a Microsoft HoloLens, an optical see-through head-mounted display (HMD), and the Unity 2017.2.1f1 graphics engine for rendering virtual content and presenting it to the user.

3.2 Tabletop Gaming Setup

Our AR setup is inspired by a two-player tabletop gaming setup, in which a real human and a virtual human sit on opposite sides of a table and take turns to move their tokens over the tabletop surface with the intention to win a rudimentary board game.

We mounted the magnetic actuator system on a 70 cm × 114 cm table surface in our experimental space (see Figure 1). On the actuated surface, we placed a board game map (24 cm × 32 cm) that contained ten designated fields for game tokens to be placed. The fields were arranged in a rectangle around the board. The size of each field was 8 cm × 8 cm. Each player started on a different field. We marked the starting positions for the VH and participant as well as the direction to move the tokens on the map. The starting positions of the tokens were located on the rightmost side of the row near each player, on opposite ends of the board. The tokens had to be moved in counterclockwise direction around the board. The player who completed a round and reached the starting position with their token first was declared the winner of the round.

A small monitor was placed next to the table to indicate whose turn it is (i.e., either the participant's or VH's) and the number of fields to move the token. We decided not to use physical dice for the tabletop game in our setup for the purpose of the experiment due to the fact that this would introduce an element of randomness to the study. Instead, we decided to use a computer-controlled virtual number wheel (similar to that of a slot machine), which was rendered in Unity and presented on the monitor. The numbers presented by the number wheel appeared random to the participants but they were predetermined and counterbalanced in our study.

For the VH to move a physical token on the tabletop surface, we attached a thin magnet (diameter: 20 mm) to the bottom of the token (diameter: 22 mm) and an unobtrusive flat IR-reflective marker on top (see markers shown in Figure 1). The tracked marker positions were streamed to the HoloLens. When it was the VH's turn, the VH first placed her right hand on the tracked position of the token, then the motorized translation stage underneath the table moved the magnet from the current position to the target position, which resulted in the token moving over the tabletop surface. Due to the smooth surface of the board game, the token slided over the table without any noticeable friction. The VH's right-hand position was updated in real time based on the tracked marker position, and inverse kinematics was applied for the upper body posture while the token was moving. Latency between the physical and virtual movements was in average 140 ms.

For the virtual human player, we used an ethnically ambiguous female character that could perform predetermined gestures and had multiple dialogue options for the game scenario. The character was modeled and rigged in Autodesk Maya and animated in the Unity graphics engine. For the VH's speech we hired a female actor to record audio for the dialogues. The gestures and dialogues were linked to the stage of the game. Since the progression of the game was predetermined, the actions could be advanced automatically without noticeable delays with minimal help by a human controller using a GUI-based desktop application. For example, while the number wheel was rotating on the small monitor, the VH moved her head and eyes to look at the wheel and responded appropriately to the result such as by saying, "Oh! I got a three." or "Yes! I am almost done."

4 EXPERIMENT

In this section we describe the experiment that we conducted to investigate differences between purely *virtual* and *physical-virtual* interactions between a VH and other objects.

4.1 Participants

34 participants (11 female, 23 male, age 18–36, average 23.6) volunteered for this paid study through an advertisement posted at the local university. 11 participants had normal vision and 23 participants had corrected-to-normal vision, either using contact lenses (8 participants) or glasses (15 participants). Participants used a 7-point scale (1=no expertise to 7=expert) to rate their level of familiarity with VR (average 4.5), AR (average 3.79), VHs (average 2.5), and tabletop games (average 5.9). 27 participants ranked their level of computer expertise as proficient or expert.

4.2 Material

In this experiment, we used the physical setup, virtual human, and Unity rendering environment described in Section 3. Verbal interaction between the participant and the VH is performed while wearing headphones of type Sony MDR-ZX110NC. Ambient noise (a sound recorded from a café) was played via the headphones to render the humming background noise of about 40–46 dB caused by the current realization of the apparatus imperceptible, assuming that it could have an effect on the results.

4.3 Method

We used a within-subjects design. Participants experienced both conditions in randomized order.

The two conditions were:

$\mathbf{C}_V$ The VH moved a *virtual* token.
$\mathbf{C}_P$ The VH moved a *physical* token.

Participants moved their physical token by themselves in both conditions.

4.3.1 Procedure. Before the experiment, the experimenter asked participants to read an informed consent form and briefed them on the study and protocol. Once participants gave the informed consent, they donned the HoloLens and went through the procedure of the HoloLens' interpupillary (IPD) calibration app. The experimenter helped participants to correctly adjust the Hololens on their head. Participants filled out a pre-questionnaire that contained demographics questions as well as questions about their prior experience with AR, VR, VHs, and tabletop gaming.

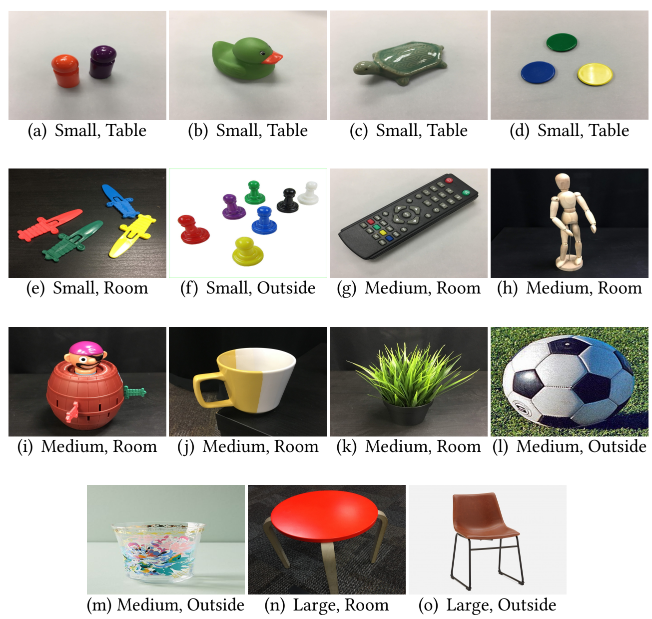
The experimenter then left the experimental room, and the participants started their first game. We used the tabletop gaming scenario described in Section 3.2. Participants played the game with the VH once for each of the two conditions in randomized order. We designed two sequences, A(1-3-3-2-2-2-3-2-2) and B(3-2-1-2-2-3-3-2-1). Depending on the sequence chosen for each game, the numbers in that sequence were displayed sequentially on the small monitor next to the table. The VH started the game both times and according to the number, players and the VH took their turns one after another. Each turn, they advanced their token by the number of steps displayed each time on the screen. In order to be comparable between both conditions, we decided that the VH should win both games.

When the game ended, participants were asked to mark the winner on a score board on a wall behind the VH, which required them to pass by the VH (see Figure 3). We included this part of the study to investigate effects of the physical-virtual interaction on the participants' locomotion behavior and passing distance when walking past the VH. Once participants made their way back to their seat, the experimenter re-entered the room and helped them take off the HoloLens and asked them to fill out a post-questionnaire. Participants then repeated the same procedure for the second condition.

Upon completion of both games, participants were asked to fill out a comparative questionnaire with also contained open questions. Participants then received a monetary compensation for their participation.

4.3.2 Subjective Measures. We measured the following items at the end of each game.

- **Co-Presence:** We used Basdogan's Co-Presence Questionnaire (CPQ) [5] to measure the level of "togetherness," being present together, experienced by the participants while playing the game with the VH.
- **Perceived Physicality:** For this measure, participants were shown photos of objects (see Figure 4) that were located inside the experimental room (see Figure 3b) or not. Their task was to rate whether or not they believed that the VH is



(a) Small, Table (b) Small, Table (c) Small, Table (d) Small, Table
(e) Small, Room (f) Small, Outside (g) Medium, Room (h) Medium, Room
(i) Medium, Room (j) Medium, Room (k) Medium, Room (l) Medium, Outside
(m) Medium, Outside (n) Large, Room (o) Large, Outside

Figure 4: Collection of physical objects presented in the questionnaire, tagged based on the size (small, medium, large) and location (on-table, in-room, outside) criteria. Participants were asked to rate their sense that the VH could physically move these objects.

able to physically move these objects using a 7-point Likert scale (1=strongly disagree, 7=strongly agree).
We grouped the object-related questions based on the following criteria:
- Object's size: *small* (e.g., game tokens and miniature figurines), *medium* (e.g., TV controller, ceramic mugs), and *large* (e.g., chairs)
- Object's location: objects that were placed on the table with the game board, objects that were place inside the experimental area, and objects that were not in the room.

- **User Experience:** We used the User Experience Questionnaire (UEQ) [41] to measure the quality of the participants' gaming experience in each condition.
- **AR Tabletop Gaming Questions:** We designed additional custom questions about different aspects of the VH and the experiment and asked participants to choose their preferred condition and explain their choice (see Table 1).

4.3.3 Behavioral Measures. During the experiment, the participants' head position and orientation tracked by the HoloLens' internal tracking system were logged. From the tracking data, we extracted the following measures.

- **Head Motion:** We measured the amount of overall head motion of the participant by calculating the length of the trajectory the participant's gaze (forward vector) traveled on a unit sphere that surrounds the head (i.e., the origin of the forward vector) during the game, and divide it by the duration of the game.
- **Dwell Time Ratio on VH:** The ratio of time devoted to looking at the VH during the game. We computed this with an angle of ±10 degrees from the forward direction obtained from the HoloLens.
- **Dwell Time Ratio on Token:** The ratio of time devoted to looking at the VH's token during the game. We computed this with an angle of ±10 degrees from the forward direction obtained from the HoloLens.
- **Clearance Distance:** The minimum distance between the participant and the VH when the participant walked toward the scoreboard (see Figure 5).
- **Walking Speed:** The mean walking speed of the participants while walking toward the scoreboard.

4.3.4 Hypotheses. Based on the related work and our study design, we formulated the following hypotheses:

H1 Participants indicate higher co-presence with the VH when they observe its ability to move a physical token ($C_P > C_V$).
H2 Participants indicate a more enjoyable gaming experience when the VH can move a physical game token ($C_P > C_V$).

Table 1: AR tabletop gaming related questions.

O1	In which condition did you feel that you were playing a tabletop game with another person?
O2	In which condition did you feel that the virtual human was able to handle physical game pieces?
O3	In which condition did you enjoy the game more?
O4	Would you like to have such a tabletop gaming system at home? Which one would you prefer?

H3 Participants transfer their experience of the VH being able to move a physical token on the table to other physical objects.
H4 Participants exhibit different (e.g., a greater passing distance, a slower walking speed) proxemic and gaze behavior in the C_P condition compared to the C_V condition.

5 RESULTS

This section presents the results of the subjective and behavioral measures in the experiment.

5.1 Subjective Measures

The questionnaire responses were analyzed using Wilcoxon signed-rank tests at the 5% significance level. Pair-wise comparisons were conducted between the physical and virtual token conditions. We performed multiple comparisons with Bonferroni correction for the object categories in the perceived physicality questionnaire. Box plots in Figure 6 are in Tukey style with whiskers extended to cover the data points which are less than 1.5 × interquartile range (IQR) distance from 1st/3rd quartile.

5.1.1 Co-Presence. The results for the CPQ questionnaire [5] are shown in Figure 6(b). As is common practice for this standard questionnaire, we computed the mean of all ratings from questions 1 to 8 with an inverted score for question 4 (Cronbach's α = .894). We found a significant difference between the two conditions (W = 325.5, Z = -2.9191, $\boldsymbol{p = 0.003}$, r = 5.38), indicating a higher sense of togetherness when the VH can move a physical token.

5.1.2 Perceived Physicality. The results for this measure are shown in Figure 6(c). We computed the sum of the ratings for each object and then the means for all the objects in each group. In this measure, higher scores indicate that participants rated the VH's ability to move physical objects in this condition higher. As expected, when comparing the physical and virtual token conditions we found significantly higher ratings in the condition with the physical token for the small objects (W = 203.5, Z = −3.058, $\boldsymbol{p = 0.002}$, r = 4.58),

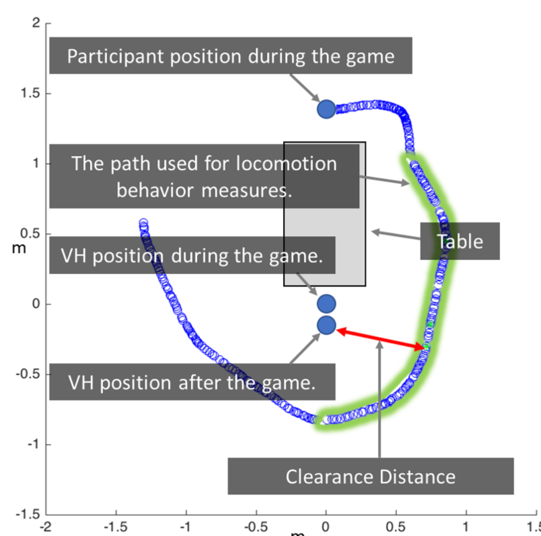
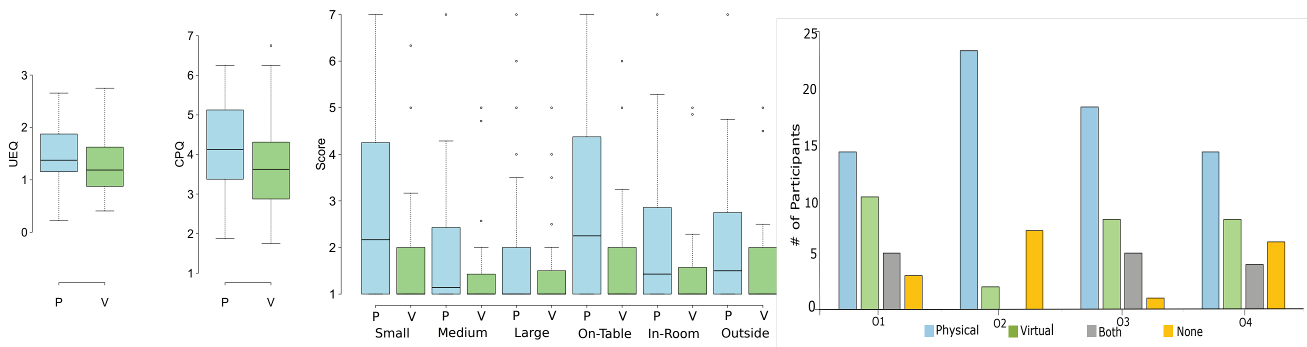
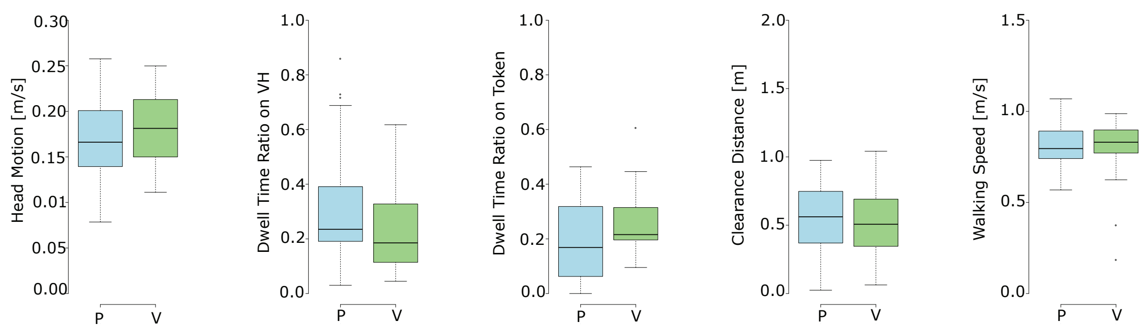


Figure 5: Example walking path of a participant. The walking speed and clearance distance were calculated from the path highlighted in green.



(a) UEQ (b) CPQ (c) Physicality (d) Gaming Questions

Figure 6: Subjective results with *P* and *V* indicating the physical and virtual token conditions, respectively: (a) user experience questionnaire, (b) co-presence questionnaire, (c) perceived physicality questionnaire with higher scores indicating a higher perception of the VH's ability to move physical objects, and (d) numbers of participants indicating preferences grouped based on their answers to each AR tabletop gaming question.



(a) (b) (c) (d) (e)

Figure 7: Results of the behavioral measures with P and V indicating the physical and virtual token conditions, respectively: (a) head motion, (b) dwell time ratio on VH, (c) dwell time ratio on token, (d) clearance distance, and (e) walking speed. Whiskers in the box plots are extended to represent the data points less than 1.5 IQR distance from 1st and 3rd quartile.

medium objects ($W = 116$, $Z = -2.482$, $\boldsymbol{p = 0.013}$, $r = 0.62$), objects on the table ($W = 200.5$, $Z = -2.954$, $\boldsymbol{p = 0.003}$, $r = 4.58$), objects in the experimental area ($W = 141.5$, $Z = -2.438$, $\boldsymbol{p = 0.014}$, $r = 4.24$), and objects outside ($W = 126.5$, $Z = -2.366$, $\boldsymbol{p = 0.017}$, $r = 4.12$). We found no significant effect but a trend for the large objects ($W = 73.5$, $Z = -1.956$, $\boldsymbol{p = 0.054}$, $r = 3.61$).

Looking at the physical token condition in more detail, we compared the effect that seeing the VH move a small physical token on the table had on the participants' sense that the VH could move other objects in the room (in the absence of direct evidence for or against this ability). We found a significantly higher probability for participants to judge that the VH could move an object on the table than anywhere else in the room ($W = 120$, $Z = -3.407$, $\boldsymbol{p = 0.002}$, $r = 3.87$) or outside the room ($W = 120$, $Z = -3.407$, $\boldsymbol{p = 0.002}$, $r = 3.87$). We further found a significantly higher probability for participants to judge that the VH is able to move a small object than a medium ($W = 120$, $Z = -3.407$, $\boldsymbol{p = 0.002}$, $r = 3.87$) or large object ($W = 91$, $Z = -3.179$, $\boldsymbol{p = 0.004}$, $r = 3.60$).

5.1.3 AR Tabletop Gaming Questions. At the the end of the experiment participants were asked the custom questions in Table 1. Based on their responses, we categorized them in four groups which were *physical*, *virtual*, *both*, and *none*. Figure 6(d) shows the number of participants in each group for each question.

5.1.4 User Experience. The results for the UEQ questionnaire [41] are shown in Figure 6(a). For this standard questionnaire, means and variances for all 26 questions are computed between -3 and 3, with scores higher than 0.8 indicating a more positive evaluation. We found a significant difference between the means in the two conditions ($W = 255$, $Z = -3$, $\boldsymbol{p = 0.002}$, $r = 4.90$), indicating a higher user experience when the VH could move the physical token.

5.2 Behavioral Measures

For the analysis of the behavioral data, we performed paired-samples t-tests at the 5% significance level for each measure. Results for all behavioral measures are shown in Figure 7.

5.2.1 Head Motion. Participants moved their head significantly more in the C_V condition (M = 0.185 m/s, SD = 0.045) than in the C_P condition (M = 0.169 m/s, SD = 0.043); $t(31)$ = -2.341, $\boldsymbol{p = 0.026}$.

5.2.2 Dwell Time Ratio on VH. We found a significant difference in the time participants dwelled on the VH between the C_P condition (M = 0.316, SD = 0.204) and the C_V condition (M = 0.239, SD = 0.153); $t(31)$ = 2.504, $\boldsymbol{p = 0.018}$. Participant spent more time looking at the VH in the physical token condition than with the virtual token while playing the game.

5.2.3 Dwell Time Ratio on Token. We found a significant effect of the conditions on the time participants dwelled on the physical (M = 0.191, SD = 0.144) or virtual (M = 0.260, SD = 0.108) token; $t(31)$ = -2.808, $\boldsymbol{p = 0.009}$. Participants looked down at the VH's token more in the C_V condition than in the C_P condition.

5.2.4 Clearance Distance. We found no significant difference in the clearance distance while walking past the VH for the C_P condition (M = 0.542 m, SD = 0.254) and the C_V condition (M = 0.499 m, SD = 0.260); $t(31)$ = 0.789, p = 0.436.

5.2.5 Walking Speed. We also found no significant difference in the means between the C_P condition (M = 0.806 m/s, SD = 0.120) and the C_V condition (M = 0.799 m/s, SD = 0.164); $t(31)$ = 0.198, p = 0.844.

6 DISCUSSION

Overall, the sense of co-presence with a VH as well as the perceived physicality of the VH and the user experience was greatly increased by observing the VH's ability to physically affect users' space. In contrast, participants' behavior seemed to be more affected by the limitations of the current state AR glasses, while their gaze behavior showed the potential of our physical-virtual table in mitigating the limitations. In the following, we discuss the results of the experiment in depth, provide potential explanations and implications.

6.1 VH's ability to affect the physical space increased Co-Presence.

Our results indicate that the sense of co-presence with the VH was significantly higher in the physical token condition where the VH exhibited its ability to affect the user's physical space compared to the virtual-only condition. The results support our Hypothesis H1.

Our findings are in line with a recent study by Kim et al. [23], in which participants reported a higher level of co-presence with a VH that walked towards a lamp (showing awareness of physical entities) and performed a plausible manipulating gesture to turn on the lamp (showing the ability to affect physical entities) compared to a VH that used a non-physical means to complete the task. The VH in both conditions in our experiment exhibited a similar level of awareness of the surrounding physical space, i.e., the VH moved her token to the designated spots on a physical game board, looked at the number wheel on the small monitor at the side of the table, and looked towards the participant when it was their turn. Hence, the increased sense of co-presence in the physical condition is likely mainly a result of the VH's ability to *affect* the physical space and less of the *awareness* of the physical space in our study.

6.2 Observed VH's physical ability on one object increased expectation of VH's ability on other objects in the physical space.

Regarding the perceived physicality, our results show a significant effect that participants were more likely to believe that the VH would be able to move other physical objects when they observed the VH move the physical token on the tabletop surface, thus supporting our Hypothesis H3. However, it is interesting that the participants were less likely to expect the VH to be able to move objects of larger size than the small physical token or when the distance of the object from the location of their observation of the VH's physical influence increased. When we asked participants about the criteria for their answers, we noticed that most of our participants applied criteria to the virtual human they would also apply to a real human. For example, one participant said "because she could move the real token, she also can move small objects," and another participant explained it with "the size of the object and how heavy it is." In other words, participants expected the VH to behave like a real human and have physical abilities in line with a real human. Along these lines, it is also interesting to note that one participant mentioned to have paid more attention to the VH's actions in the virtual token condition because the VH was perceived to be able to cheat more easily with the virtual token than with the physical token.

6.3 Physical-virtual table improved the user experience of AR game.

The UEQ questionnaire is designed to assess user experience in terms of attractiveness, perspicuity, efficiency, dependability, stimulation and novelty [41], which are important elements of an engaging game. The subjective responses for this UEQ questionnaire, the game-related questions listed in Table 1, as well as the informal feedback collected from our participants all are in support of our Hypothesis H2 that the physical token condition would result in a more enjoyable experience. Many of our participants described their interaction as fun, interesting, and exciting. It should be noted that it appears that the limited field of view of the HoloLens may have worked in advantage of the physical token condition, since it satisfied the efficiency and dependability aspects of the UEQ more than the virtual condition according to some of our participants.

6.4 The physical-virtual table mitigated the usability issue of small augmented FoV.

The results for the behavioral measures partially support our Hypothesis H4. We found significant differences between the two conditions in participants' head motion behavior (amount of head motions, dwell time on VH, dwell time on token) in favor of the physical token condition. These differences could be caused by the relatively small augmented field of view of the HoloLens used in this study. Similar to what was described in a recent paper by Lee et al. [28], participants in our study could not see both the VH's face and the virtual token at the same time during the game. Thus, they needed to keep moving their head up and down to see the progress of the game as well as maintain the social interaction with the VH. Whereas, for the physical condition, they could just look down with

Table 2: Summary of the hypothesis testing results.

	Hypothesis	Statistical test	Results
H1	Participants indicate higher co-presence with the VH when they observe its ability to move a physical token ($C_P > C_V$).	Wilcoxon signed-rank test	**Accepted** ($p < .01$)
H2	Participants indicate a more enjoyable gaming experience when the VH can move a physical game token ($C_P > C_V$).	Wilcoxon signed-rank test	**Accepted** ($p < .01$)
H3	Participants transfer their experience of the VH being able to move a physical token on the table to other physical objects.	Wilcoxon signed-rank test	**Accepted** Small objects ($p < .01$) Medium objects ($p < .05$) Large objects ($p > .05$)
H4	Participants exhibit different (e.g., a greater passing distance, a slower walking speed) proxemic and gaze behavior in the C_P condition compared to the C_V condition.	Paired-samples t-test	**Partially accepted** Head motion ($p < .05$) Dwell time ratio on VH ($p < .05$) Dwell time ratio on Token ($p < .01$) Clearance distance ($p > .05$) Walking speed ($p > .05$)

their eyes to check the position of the opponent's physical token while keeping their head up. Once participants observed the VH's hand touching and moving the physical token, they could mentally connect the VH's visible upper body behavior with the moving physical token seen in the unaugmented periphery of the HoloLens. The reduced dwell time on the token and increased dwell time on the VH in the physical condition seems to match this explanation. Considering the weight of current-state AR glasses, reducing the amount of required head motion to keep track of large virtual content in close proximity of the user could greatly improve the user experience. In this regards, participants' strong preference of the physical condition, as well as the highly rated user experience, might to some degree result from the reduced head motion.

Based on related work (e.g., [2, 24, 28]), we initially expected to see more realistic locomotion behavior for the physical condition, e.g., keeping a more considerable clearance distance as well as slower walking speed. However, we did not find significant differences between the conditions on locomotion behavior. Interestingly, most participants stated in open-ended questions that they were more cautious passing by the VH in the physical condition compared to the virtual condition, which suggested a possible decrease in walking speed and an increase in clearance distance. However, the effect was not shown in their actual behavior, rather we found that five participants even walked *through* the VH instead of around it. We found a possible reason for the observed locomotion behavior in the participants' comments. Some participants stated that they did not notice the VH standing in their way when they walked towards the scoreboard, which again resulted from the small augmented field of view. Similar results have been reported in recent work [28], in which vibrotactile feedback of a VH's footsteps increased co-presence with the VH but did not affect users' locomotion behavior in AR, while the locomotion behavior heavily depended on the AR view condition.

6.5 Limitations and potential of the physical-virtual table

The apparatus presented in Section 3 showed a reasonable performance as indicated by the aforementioned high sense of physical-virtual interactivity judged by the participants in our experiment. During debriefing, when asked about the potential cause of the physical token's movement, 10 participants described it with terms such as *mechanical*, *external force*, or *motorized*, while 15 participants described it as *magnetic*. The fact that most participants came up with a potential computer-controlled cause of the physical movements might be related to the overall high level of computer expertise among our participant population. It would be interesting to compare our results in this experiment with children and participants with less computer experience in future work.

A limitation of the current realization of the prototype is the humming background noise by the motors of the translation stage. During the debriefing, when asked whether they heard sounds while playing the game, 25 participants stated that they did not perceive any noise related to the movement of the token, while the remaining 9 participants perceived some noise coming from the table and/or token. In our study, we used headphones to compensate for the background noise of the system, but for future realizations of such actuator systems for tabletop gaming and related experiences, we suggest integrating a noiseless translation stage.

Overall, 23 participants indicated that they enjoyed the condition with the actuated physical token more than the virtual condition, and 18 participants indicated that they would like to have such a tabletop gaming system with actuated physical game tokens at home. We believe that tabletop mechanical actuator systems as described in this paper have much potential for a wide range of tabletop gaming scenarios including serious games such as strategic or tactical wargaming scenarios, e.g., based on an AR Sand Table (ARES) [1] and related efforts.

7 CONCLUSION

In this paper, we investigated the effects of a virtual human's physical influence on participants' perception of the virtual human and its abilities. We described an apparatus based on a motorized translation stage capable of magnetically moving small physical objects over a tabletop surface, while the physical source of the movement is hidden from an observer's view. Instead, in this setup, users wear a HoloLens and see a virtual human reach out with its hand and move the physical object. Based on this setup, we designed a basic interaction scenario, a tabletop board game, and performed a user study where participants played the game twice, each time with the virtual human either moving a virtual or a physical token throughout the game. Our results show significant benefits of the virtual human being able to move a physical token with respect to a positive impact on participants' sense of co-presence, physicality, and the virtual human's abilities.

Future work may focus on extending the presented setup to the third dimension, i.e., moving physical objects not only on the tabletop surface but integrating an electromagnetic mechanism to levitate them in mid air (e.g., see [27]). This would enable situations where the virtual human could pick up an object from the tabletop and set it down again, such as when picking up and rolling dice.

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