An Exploration of Exertion in Mixed Reality Systems via the “Table Tennis for Three” Game

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Abstract

Humans experience their physical and social environment through their bodies and their associated movement actions. However, most mixed reality systems approach the integration of the real with a virtual world from a computational perspective, often neglecting the body’s capabilities by offering only limited interaction possibilities with a few augmented tangible objects. We propose a view on mixed reality systems that focuses on the human body and its movements, because we believe such an approach has the potential to support novel interaction experiences, as explored by a prototypal gaming system that was inspired by exertion actions exhibited in table tennis. “Table Tennis for Three” enables augmented bodily experiences while offering new opportunities for interaction, such as supporting three players simultaneously across geographical distances. This case study offers an exploration of the role of the human body and its associated movement actions in mixed reality systems, aiming to contribute towards an understanding of the use of exertion in such systems. Such an understanding can support leveraging the many benefits of exertion through mixed reality systems and therefore guide future advances in this research field.

Keywords: Augmented reality, videoconference, table tennis, ping pong, Exertion Interface, physical, tangible, sports, proprioception, social, phenomenology, body, gross-motor interaction, full-body interaction.

Introduction

Mixed reality systems aim to make use of the benefits of a virtual domain in combination with the advantages of a physical world. This is often achieved through visually augmenting tangible objects, meant to be grasped and manipulated with hands and fingers, in order to access the embedded digital information [2, 3, 17]. Such an interaction approach has been favored in many work-related scenarios in which the focus rests on the virtual content while the body's involvement is only dealt with peripherally. However, other scenarios exist in which the entire body and its movements play a significant role. For example, physical games such as sports put the human body and its capabilities for gross-motor interaction at the centre of the experience. These physical games are important, as they have been attributed with social, physical and mental health benefits [14, 15, 29, 34], in particular their potential for increasing the energy expenditure to address the obesity epidemic has been highlighted [14].

This potential of the human body, however, is not very prominent in many mixed reality systems, exemplified by the numerous mixed reality applications that feature tangible objects, which predominantly afford fine-motor interactions with hand and fingers [32]. Such augmented objects can facilitate enhanced experiences in terms of dealing with virtual information by allowing the user to grasp, examine and rearrange them, however, their afforded interactions represent only a limited subset of expressive actions the human body supports, as people experience their environment through their bodies and interact with embodied others by utilizing their potential for action through movement [24].

In order to allow the body and its associated movement actions to take a more central role in mixed reality systems, the proposal is made here to reconsider the physical aspect of the real world in these systems and examine their potential for supporting the wide variety of bodily movements users can engage in. Focusing on the movements can allow for being sensitized to the affordances of the environment as well as artifacts to support bodily actions and allow for expressive interactions, which in turn could highlight opportunities for technological augmentation otherwise not readily evident. In order to advance the exploration of such an approach, we have developed a prototypal gaming system inspired by the exertion actions exhibited in table tennis. This investigation represents an approach to mixed reality systems in which the human body plays a central role in the design for the interaction. It is presented in the context of an exertion game, a game that requires intense physical effort from the player [27], in order to highlight the approach’s potential to offer distinct benefits. The case study investigated describes “Table Tennis for Three”, a physical game for three distributed players. It is aimed at telling a story of how a focus on the body and its movements relate to interaction design. The game development drew inspiration from table tennis, and the user plays with a real ball, bat and table, however, the gameplay experience is quite different to traditional table tennis. The virtual augmentation utilizes a videoconferencing component to allow for distributed play while the affordances of tangible objects support movements that facilitate maintaining the benefits of physical play. This approach can facilitate novel user experiences such as supporting three geographically distant participants, contributing equally in the game, a scenario not easily achieved in traditional table tennis. Initial investigations with users have suggested that the game can facilitate engaging and social situations similar to table tennis, and the use of bat and ball have inspired to name the game “Table Tennis for Three”.

Related Work

The consideration of the human body in human-computer interactions can be grounded in prior work that goes beyond the immediate application in digital domains. Merleau-Ponty’s phenomenology lays a foundation by introducing a perspective that the human body is mutually engaged with the mind and that this intertwined connection is the primary access to “being-in-the-world” and therefore determines how we perceive and interact with our environment and other embodied beings [24]. This “being-in-the-world” is derived from Heidegger’s work, who stresses a role of the body and its actions within the environment in regards to the notion of meaning making, arguing that meaning only exists because humans act with their bodies and turn this action into meaning. Furthermore, humans live in a social world, which means these actions are not meaningful per se, but only meaningful through the social context, highlighting a social component. Researchers that stress the role of the human body in a digital world draw on these philosophical investigations, for example Winograd et al. argues for a more nuanced view on the embodied user when interacting with computers [35]. McCarthy and Wright see technology as experience that is featured in an embodied world, arguing for an opportunity to positively influence the design [23]. Dourish identified an embodied view in the tangible and social computing systems developed in the 1990s [10]; he suggests combining their advantages because he believes that the features of technological systems are related to the features of social settings, following Merleau-Ponty’s perspective. In sum, the interplay between the body and its movements in relation to the world humans interact in is grounded in early philosophical investigations, and has been applied to interactions with computers recently, which drew attention to a social component that seems to be integral. The proposed work has been using this theoretical lens to investigate the phenomenon.

The relationship between physical affordances of the environment and engagement with technology as well as the role of the body in these experiences has been explored mainly in the context of games. Lindley et al. have found that the game's nature can change when players are involved in bodily actions, in contrast to button presses, from a traditional virtual game experience of "hard fun" to more social play [22]. De Kort et al. promote the consideration of embodied play because they believe players have an intrinsic need to experience their physical environment kinesthetically [9]. They propose a relationship between physical environment and virtual gameplay while extending this view by proposing "sociality characteristics" for games, which includes a consideration of exertion actions, as they can "radically" impact social play [9]; however, the authors fall short in providing example applications for their claims. Moen [25] highlights the role of free-form movements in mixed reality settings and presents a framework for kinesthetic movement interaction, arguing that technological augmentation can support novel experiences, but the author concentrates on single-user interactions.

Fish'N'Steps is a social approach to combining physical bodily actions with virtual content to enhance a healthy activity. It is a mobile application that is aimed at encouraging participation in walking activities via means of social comparison [21]. The proposed system works in combination with a pedometer to motivate an increase in a participant's daily energy expenditure. It focuses on the users' everyday environment and their bodily actions in it, in contrast to dedicated exercise sessions. Furthermore, the system separates the physical activity from the social activity quite distinctly: only after the participants walked all day, they can share their progress through a fish tank metaphor

displayed on a screen in an office, where their bodies rest while they assess their relative progress.
Consolvo et al. presents another distributed pedometer-based system implemented in a mobile phone [7]. Based on a study, the authors have identified design requirements that include aspects regarding the body, the users' environment, and the virtual augmentation. They found that combining the physical with the virtual world throughout the users' entire daily life is not necessary, but rather that this combination can offer benefits in time-specific situations, suggesting that a mixed reality approach could be suitable for dedicated exercise sessions.
Systems that combine real world physical exertion with the virtual aspects of a videoconference have suggested the possibility of a social facilitation effect. For example, exercise bikes have been networked to allow for distributed races in a competitive environment. The bodily component suggests the use of physiological data to enhance the distributed experience, as participants reported that visualized heart rate from a remote rider motivated them to cycle faster [6]. The presence of a remote participant appears to affect the exertion performance, however, in exercise bike cycling the participants can not interfere with one another physically, as for example in many team sports, in which players can actively prevent their opponents from achieving the game's goal [33]. This aspect of the shared experience is missing in networked bike riding; however, it has been explored in Breakout for Two [27]. Breakout for Two is a synchronous exertion game for two players with an integrated video communication channel, in which participants can chose between an active and passive style of playing. An evaluation showed that players were able to form a social bond between one another despite the geographical distance between them, and that the exertion activity contributed to this outcome. What has yet to be explored is if the effect was specific to the type of exertion game and the two-location setup.
Furthermore, it is still an unanswered question what role the mixed reality environment plays in these exertion activities.

The game of table tennis has inspired other research projects before, and a few approaches have presented a mixed reality approach around this sportive game [18-20, 36]. Most of these implementations focus on the demonstration of the technologies' capabilities, showcasing how mechanical and computational advances can simulate certain aspects of table tennis, for example force-feedback [19]. The outcomes of these projects suggest that simulating and recreating a traditional bodily game such as table tennis is still technologically challenging; a networked version that enables a recreation of a traditional table tennis experience might therefore currently not be feasible technically and financially.

In sum, research suggests that the consideration of the human body and its physically effortful interactions in interactive systems can facilitate beneficial experiences. Most utilized approaches are based on an embodied perspective that highlights the importance of the users' body being situated in a physical environment, interacting with other embodied beings. However, there is a limited understanding of what role a mixed reality environment plays when bodily actions are augmented with technology. The approach taken here is to advocate an appreciation of the physical environment for the support of the human body in order to identify opportunities for technical augmentation that provide a benefit to the experience. Through a case study, this notion of an increased focus on the body's actions and their use in a physical world while being engaged in an interactive experience is explored. The described investigation highlights the potential for novel experiences such as unique social support in terms of number and geographical location of participants, difficult to achieve without technological augmentation. Investigating this can contribute towards an understanding of the use of exertion in mixed reality systems, which can support the leveraging of the many benefits physical activity affords, guiding future advances in this research field.

Table Tennis for Three

The following section describes “Table Tennis for Three”, our case study application that exemplifies a body-centric view of mixed reality approaches. Table Tennis for Three is a mixed reality game that draws inspiration from the exertion actions exhibited in table tennis. Its aim is to encourage players to be physically active and exert themselves, as research suggests that the involvement of the body in such gaming interactions can facilitate emotional and social experiences [5, 22]. The technological augmentation enables novel aspects not possible in traditional physical games such as table tennis: here it is the support of distributed users, as well as a scaling to three players who can participate equally in the gaming action.

As the game development drew inspiration from table tennis, and the user plays with a real ball, bat and table, the name Table Tennis for Three was chosen, however, the gameplay experience is quite different to traditional table tennis. This novel gameplay demonstrates that enabling such enhanced experiences like supporting three geographically players equally do not necessarily require the full extent of computational augmentation, as prior simulation approaches might suggest. The described case study shows that thoughtful design can result in systems that enable novel and engaging experiences similar to – but not identical – traditional non-augmented experiences offering additional benefits. With our approach, we are aiming at inspiring future research in this area, while demonstrating that implementation is possible within the limits of current technology.

The Table Tennis for Three Experience

Fig. 1. Table Tennis for Three.

The following describes the users' experience when playing Table Tennis for Three. Each player has a bat and a ball and steps up to the table. The table is set up so that the ball can be hit against the vertically positioned opposite half of the table (Fig. 1). This setup is familiar to table tennis players who practice on their own by playing the ball against the board. The vertical part of the table is painted white to also serve as projection surface for a videoconference of the other two players. Projected on top of the videoconference are eight semi-transparent targets that players have to hit with their ball (Fig. 2).

Fig. 2. The semi-transparent blocks overlaying the videoconferencing component.

These targets, or blocks, “break” when hit by the players. The blocks are synchronized across the three tables, so the other players see the same block layout and the same block states (Fig. 3).

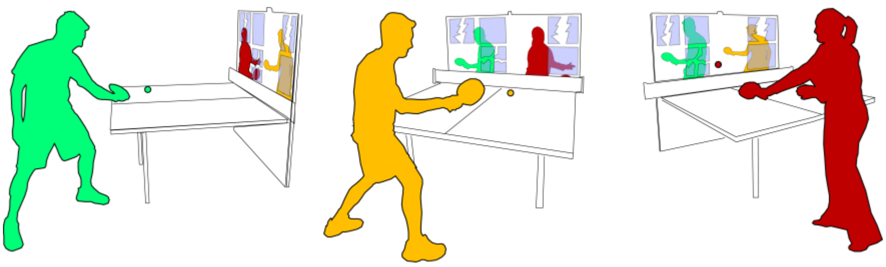

Fig. 3. The blocks are shared amongst the locations.

If a block is hit once, it cracks a little. If it is hit again (regardless of by which player), it cracks more. If hit three times, it breaks and disappears, revealing the underlying videoconference completely: the player has broken through to the remote players. However, only the player who hits the block the third and final time makes it disappear and receives the point. This adds an element of strategy to the game: a player can try to snatch away points by hitting blocks that have already been hit twice by the other player. Each broken block scores one point, and once all blocks are cleared, the player with the most points wins the game.

Design of Table Tennis for Three

Choice of Tangible Equipment

Supporting exertion activities in interactive entertainment is often facilitated by a combination of interfaces that facilitate gross-motor actions and virtual game content. Gross-motor activities need to be afforded by the interface, but also recognized by the computer in order to affect the gameplay and enable the interactive component. Table Tennis for Three uses a traditional table tennis bat and ball on a physical table as the interface to the virtual gameplay, supported by a detection system that detects the ball's impact. The following section justifies the choice of the tangible equipment in Table Tennis for Three.

Supporting Bodily Skill Training

The need to facilitate gross-motor actions to encourage exertion can be supported by tangible objects that afford certain movements known from traditional bodily interactions, such as the use of bats, racquets and balls in sports: users are already familiar with the movements these objects are intended to support. Although most sports equipment appears to afford only a small subset of a person's entire range of movements, they can still require a lifetime of training to be mastered, for example a table tennis bat. This characteristic of facilitating the acquisition of bodily skills has been described as a key element of an exertion interface [27]. In addition to supporting bodily skill training, such sport equipment offers a familiarity that could reduce participants' hesitations to invest exertion during the activity.

Utilizing Existing Sport Advances

Using existing sports equipment such as the table tennis bat also utilizes the ergonomic and material advances years of sports research has produced in making such devices suitable and effective for athletic training and exercise. Due to these reasons, Table Tennis for Three uses a traditional table tennis bat that has not experienced any technical augmentation that would change its characteristics for the exertion activity.

Uncertainty of the Real World

Although several other augmented systems that are inspired by table tennis replace the ball with a virtual pendant [19, 36], Table Tennis for Three uses a real ball. Using a physical instead of a virtual ball enables a simplified ability to support a notion of uncertainty that is characteristic to sportive experiences. In sports activities that require a ball, the unpredictability of the ball is a significant element of what makes the game interesting. The ball might hit the edge of a racquet, fly off in unexpected ways, bounce off the top of a net in surprising ways, or dance around the rim of a basketball basket, creating sensations of anticipation within the players and the audience. The use of an oval ball in some sports such as rugby emphasizes this unpredictability by artificially increasing opportunities for uncertainty, instantiated through notions of surprise exhibited by the players. It should be noted, however, that the bounce of a ball could be predicted computationally, and is therefore not completely unpredictable. However, in the course of bodily actions in an exertion sports environment, the speed involved as well as the many other factors that influence what happens next make many actions of the ball unpredictable for the players. Predicting a bounce is a skill players practice over many years, however, small changes within the environment often create unpredicted situations that result in surprise, possibly affecting the outcome of the entire game. For example, one can imagine the unpredicted bounce of a ball off a defender in soccer, which leads to an own goal, resulting in a win of a team that was inferior. Such surprises are characteristic for sports, and contribute to the fascination it has to so many people, as it can facilitate very emotional moments.

This notion of surprise has been acknowledged in traditional exertion activities [8] as well as augmented mixed reality systems [31]. Mixed reality systems, in contrast to exclusively virtual systems, are in a unique situation of being able to foster this notion because they are able to utilize the elements of the physical world that are often supporting this effect. In virtual game play, these surprise encounters need to be artificially introduced through deliberate programming, as an element of chance is required in most games. Game creators have to take special care in finding an engaging balance between believable chance and randomness as experienced by the players [30]. For example, in a game such as the Nintendo Wii Sports Tennis [1], the ball in the virtual world could be affected by a programmed element of chance; but such an approach might appear to be generic by the players, as the ball will never bounce off the physical environment that the users act in and experience with their bodies, enforcing the sense of a strict separation between the virtual and the physical world. The ball will also not bounce off the avatar’s racquet frame in unexpected ways because the virtual world is programmed not to support this, but

even if it would be accommodated for in the design, the experience will be “fundamentally different”, as players might not believe the probability by which it occurs, and rather assume a bug in the software [13] than it being a core element of the game, possibly eliciting emotions of frustration rather than disappointment as a response to ‘bad luck’. We believe that this concept of supporting uncertainty of the real world in virtual applications can contribute to the conceptual dissolving of the separation between the physical and the virtual world, and see it within the tradition of Merleau-Ponty’s stance of considering an embodied mind rather than a strict separation between the body and the mind.
The notion of uncertainty can also affect social aspects in mixed reality systems, important in the design of Table Tennis for Three, which supports audio and video communication between players. Gaver claims that the physical environment can provide affordances for social interaction [13], which might suggest that mixed reality systems have an advantage over purely virtual systems in terms of social support. Hornecker implies that “the richness of bodily movement” in combination with tangible objects is particularly beneficial for social interactions [16]. The afforded exertion activities in Table Tennis for Three are aimed to facilitate the probability of surprise occurring as well as to amplify the outcome of this uncertainty. Tangibility can support uncertainty without exertion, however, we believe the extensive, fast and forceful movements exhibited in exertion activities enable as well as amplify these surprising moments. The social sharing of the resulting emotions might amplify their effects further, supporting the notion that there is a unique role for social support in mixed reality systems.

Supporting Proprioception and Force-Feedback

Physical exertion in Table Tennis for Three is achieved through the use of gross-motor activity. Although exertion can also be facilitated through non-physical, non-contact systems such as the

Sony EyeToy [11], the utilization of tangible objects and the physical environment as proposed in mixed reality systems can offer unique benefits. Affordances of physical objects can support the users' sense of proprioception. This sense of proprioception is an important element in movement-based interaction [25]. For example, in a mixed reality environment, an extension of a player's arm, for example a racquet, affords the user with a different sense of where this extension is located in terms of his/her other body parts than in a virtual environment, as this mapping is achieved only through visual means. In an exclusively virtual environment misalignment between movement and object might occur, a problem particularly important in the context of fast sportive bodily actions. Furthermore, the use of physical objects enables an inexpensive use of feedback that is difficult to achieve with conventional force-feedback technology, as current developments indicate. For example, research has attempted to simulate the impact of a table tennis ball in a virtual environment [19], and the results show that simulating the variety and intensity of a ball and bat impact is not a trivial problem.

Avoiding Complex Equipment such as Head-Mounted Displays

Solutions that utilize a virtual ball often require the user to wear a head-mounted display [19, 20]. Such a head-mounted display often includes a camera that enables the blending of the physical world with the virtual objects, setting the stage for a typical mixed reality system. These head-mounted displays suffer from technical limitations, such as limited resolution, viewing size, physical size, weight, and uncomfortable fit to the wearer's head [2]. In regards to exertion, it should be noted that these devices also possibly restrict the users in their bodily movements. Fast head movements might dislocate the device and lead to a misalignment of the viewing area. The cable providing power and video source data might limit the user's limb movements and might also restrict the action radius of the body to the length of the cable. Furthermore, the head-mounted display obscures the eyes of the users so they are not visible to their peers, limiting opportunities for eye contact as social cues. The use of a physical, instead of virtual ball allows abdicating complex equipment such as head-mounted displays and their associated limitations.

Implementation

The implementation of the system can be described from three different perspectives: the detection mechanism, the social communication channel, and the gameplay. Detecting the outcomes of the bodily actions is facilitated by indirectly measuring the exertion activities. This is achieved by looking at the result of the exertion action applied to the ball. By measuring the location of the impact of the ball onto the vertical part of the table, an input mechanism based on exertion is facilitated to control the game. Social communication is enabled through a videoconference that includes an always-on audio channel, and the gameplay brings the remote stations together by enabling a shared space for all three players.

Impact Detection Mechanism

In any bodily game, there are two possible ways to detect and measure the exertion exhibited by the players. The exertion could be measured directly through physiological means, often acquired through equipment worn by the user. However, such an approach might restrict the players in their movements. Therefore, the exhibited exertion in Table Tennis for Three is measured indirectly: the outcome of the bodily activities is measured by sensing the results applied to the ball. Initial investigations examined tracking the ball with video capture technology; however, as table tennis balls can reach speeds around 100 km/h, conventional cameras with a frame rate of 25-30 frames per second (fps) were not fast enough to capture the balls. High-speed cameras were consequently used that captured up to 500 fps, however, the image analysis required CPU power that was beyond what the high-end, but still commercially standard PCs we used were able to process with the amount of data generated. Furthermore, a high shutter speed of the cameras was required in order to acquire a sharp outline of the ball for easy segmentation by the algorithm. Unfortunately, bright illumination of the area above the table affects the videoconference projection, which benefits from a darker environment. The initial setup therefore required a balancing act between these various components. Although most of these restrictions are of a technical nature and might be addressed by advances in equipment, the initial vision-based system was limited by these compromises. Therefore, an alternative system that uses an audio-based approach was developed to overcome many of these restrictions.

The final design consists of eight piezoelectric sensors that are attached to the rear of the backboard in locations corresponding to the gameplay blocks projected on the front of the backboard (Fig. 4). The sensors detect the sound vibrations in the wooden board created by the ball striking it. This approach is similar to the system described by Ishii et al. [18]. In their system, any impact with the

surface is located through interpolation. However, as this implementation is primarily used for visualization, any inaccuracy does not affect the interaction the same way as in the Table Tennis for Three game, where a false detection can determine the outcome of the game negatively and hence significantly impact upon the user's experience. Therefore, the number of sensors in the Table Tennis for Three game was increased to eight and their location was aligned to the game blocks projected on the front of the board to increase accuracy and detection rates.
It could be envisioned that this approach scales to accommodate more game 'targets' to be sensed. However, an increase in piezoelectric sensors requires special data acquisition hardware, as most conventional boards only accept a limited number of analog signal inputs. The Table Tennis for Three system uses a commercial data acquisition board that accepts up to 10 analog inputs; we have used 8, one for each target. Each of the eight inputs is sampled with 25 kHz, which provides an adequate resolution to reliably detect even fast hits. The sensor data is first squared to deal only with positive values and then filtered by custom-made software. This was necessary in order to eliminate other potential trigger sources such as reflecting noises from the edge of the board and impact sounds from the ball hitting the horizontal part of the table. The rigging of the vertical part of the table also affected the sound characteristics of the board as it dampened the sound distribution across certain parts. If the signal strength was above a certain threshold over a specified length of time, it was considered to be an impact. The sensor that first received the vibration signal then determined the location of the impact. Although the analysis did not consider an intensity value, it could be envisioned that the captured data could be used to also measure how hard the players hit the ball, similar to the approach described by Mueller [26].
Detecting the location of the impact with sensors attached to the back of the interaction surface shields the involved technology away from the exertion actions of the user. This has several advantages: the delicate sensor technology is not exposed to potential damage caused by the ball, and the player is also not

seeing possibly intimidating technological artifacts that might hinder the use of excessive force out of fear of breaking the equipment.

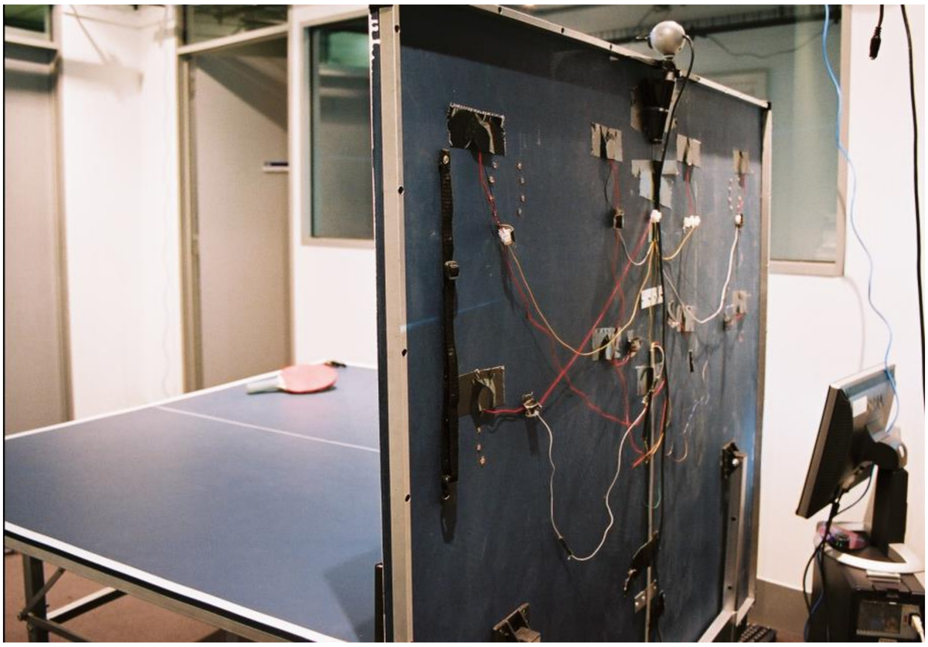

Fig. 4. Sensors attached to the back of the Table Tennis for Three system.

Videoconferencing

The videoconferencing component, together with the gameplay implementation, comprises the virtual aspect of the Table Tennis for Three system. It is independent from the other technical aspects of the system, because developing a videoconferencing system is not a trivial task, and many commercial and research systems claim to offer the best compromise between bandwidth restrictions and image and audio quality. These implementations balance the most efficient compression codecs with en- and decoding CPU requirements, deal with varying network lags and congestions, provide circumventions for firewall issues, and aim to reduce noise-and echo effects. In order to utilize the latest advances in videoconferencing technology, the videoconference implementation in Table Tennis for Three is a separate application that acts independently and is placed as a window behind the gameplay application that is half-transparent. The gameplay software is programmed with a transparent background, which allows the players to see the underlying videoconference.

In the current setup, the videoconference resolution is 640x480 pixels with 25 fps to support the fast moving actions exhibited by the players during game play. The images are captured by consumer webcams. The audio is captured with Bluetooth headsets the players are wearing. Initial experiments with directional microphones did not achieve encouraging results as the impact noise of the table tennis ball was often captured on top of the players' voices. Furthermore, the bodily movements facilitated by the game resulted in the players changing their physical location much, so that talking when collecting balls behind the table or at the remote end of the room was barely picked up by stationary microphones. Therefore, players are asked to wear a Bluetooth headset, which acts as a low-cost wireless transmission device in Table Tennis for Three. Due to the fact that only the microphone functionality of the headset is used, the user can also wear the device on a shirt's collar, often preferred when compared to the time-consuming adjustment necessary if positioned on the ear. The sound effects of the game as well as the audio from the remote ends are sent to speakers located under the table in order to allow spectators to hear as well. This setup however often created echo issues, with the microphone picking up the audio coming from the speakers. An alternative setup would be to route the audio through the headset to avoid this issue. However, although several Bluetooth models were trialed, none were very suitable due to awkward fit to different ears, hence only the microphone functionality is used and users can choose to either wear the device on their ear or on their collar.

Gameplay

The game aspect of Table Tennis for Three is implemented as a separate application, which synchronizes its game state through a dedicated server component, programmed as a Windows XP application. Each playing station acts as a client in this star-shaped architecture, informing the server of any changes. The server is responsible for distributing the latest block states and score changes to all other clients. In case of varying networking conditions that need to reach across various implementation restrictions, an HTTP fallback mechanism can be utilized in case certain network ports are blocked due to firewall settings. Although the system has not been tested across large distances, the aforementioned provisions make an Internet-based implementation feasible.

This implementation section showed that Table Tennis for Three exemplifies a mixed reality system, as it combines the advantages of the real world with the advantages of virtual objects. Designing for such mixed reality systems requires not only technical knowledge how these aspects can be implemented individually, but also how they can work together as the physical domain needs to be accessible to the virtual domain and vice versa. This bridging between the physical and the virtual domain in Table Tennis for Three is facilitated by the gameplay: the detection mechanism that senses changes in the physical world triggers changes in the virtual world. In contrast to mouse and keyboard controlled interactive experiences, the focus in Table Tennis for Three lies on the significance of the user's actions in the physical world: the exertion the players invest is a significant contribution to the interaction with the system, and the gameplay needs to consider this. The invested exertion is not a by-product of the intention to control the system, it is an elementary part of the interaction experience: it is 'the action'.
By highlighting these three key design implementation elements of Table Tennis for Three, we aim to tell a story about exploring the

role of the human body and its associated movements actions in mixed reality systems. We hope to inspire future developments that aim to utilize the benefits in novel ways, using Table Tennis for Three as an example of how such a mixed reality system can provide users with new experiences otherwise not available without augmentation.

Feedback from Users

A quantitative analysis with 41 players of Table Tennis for Three suggest that engagement can occur in this exertion game, even though the three players are in different locations (for more details see [12, 28]). The players reported that they had "fun" and found the game engaging. The evaluation using questionnaires and interviews indicated that the participants enjoyed playing the game and that they could see such a networked mixed reality game being helpful in facilitating rapport between people who are physically apart but want to stay in touch. In particular, they expressed a sense of "playing together" and commented on the fact that it "gave them something to talk about". Several players said that the game created a sense of social rapport, and that they were excited about being able to play together over a distance, wanting to play again. The affordance created by the shift towards the physical world in the design of the game appeared to support participants' engagement and interaction, and most players reported that they considered the activity a workout and that they forgot the world around them when playing, comparable with notions in traditional table tennis. The choice of table tennis equipment appeared to support bodily skill training, as three participants asked if they could practice on their own after the interview. During the interviews, players compared the game to their previous table tennis experiences, noting that they were able to use some of their skills, however, other requirements, such as playing the ball high to hit the upper blocks, require tactics different to traditional table tennis. The uncertainty of the real world was exemplified by many balls hitting the edge of the table or bat, flying off in unexpected ways, which facilitated laughter by the participants, contributing to a social atmosphere.

Future Work

The investigation of Table Tennis for Three is aimed at contributing to an understanding of what it means to focus on the human body and its movements in mixed reality systems, demonstrated by an example application. It is only an initial exploration that is intended to highlight certain aspects that such an approach can support. Further work is needed to generate a theoretical framework that frames this view in regards to other mixed reality approaches and identifies similarities and differences. For example, the benefits of focusing on the human body and its movements could be investigated empirically; this would provide insights into how mixed reality systems can be approached in terms of evaluation. Furthermore, future work could also detail the impact of such systems on embodied social experiences. The Table Tennis for Three game is also a demonstrator for the potential of mixed reality systems to support social interactions when geographically distant. Alternative scenarios could entail asynchronous instead of synchronous embodied experiences, another challenging area for future work. Further scaling of the approach beyond three participants could also shed light on the role of the body in massively large mixed reality systems. In such large environments the participants are likely to not simultaneously engage in bodily actions, and a spectator role might need to be considered, as exertion games can facilitate performance aspects [4]. Accommodating many participants and spectators can result in experiences similar to traditional sports events, and the role of augmenting movements made by thousands raises interesting questions for future mixed reality systems.

Discussion and Conclusions

With our work, we explored the role of the body and its associated movement actions in mixed reality systems through the use of a game named Table Tennis for Three. We have argued that when integrating the real world with the virtual world, the human body offers opportunities that should play significant roles to be considered in the design of such systems. By appreciating the body's movements when experiencing the environment, physical objects and other human beings, technological augmentation can facilitate novel experiences and support engaging interactions. To support this, we have proposed that the physical world aspects in mixed reality systems can take on a central role in supporting such embodied experiences, contrasting traditional development efforts that often start with a view on the virtual component. Our exploration suggests that a consideration of physical characteristics, for example through tangible equipment, can facilitate aspects such as bodily skill training, leverage existing sport advances, utilize uncertainties of the real world, support proprioception and force-feedback in a low-cost way, and reduces the need for complex equipment such as head-mounted displays, as featured in more traditional mixed reality systems. To demonstrate how such an approach can shape the design of systems, a prototypal game was presented that was built around exertion movements, inspired by the game of table tennis. The prototype does not aim to simulate a table tennis game as accurately as possible, but rather offers a unique experience for the participants, not achievable without augmentation. Table Tennis for Three explores how bodily movements can be supported by the physical environment and physical game objects, and how technological augmentation can enable novel experiences, in this case the support of three players engaging in gameplay simultaneously while being in geographically distant locations. Furthermore, the system also explores how such an approach can have implications for an implementation process, as many traditionally difficult technical issues such as force-feedback and the overlaying of virtual content through head-mounted displays are circumnavigated through a focus on the embodied experience. Also, shielding the detection technology away from the user presents an approach specifically suitable for exertion actions, as the bodily movements could damage equipment as well as possibly influence users in their interaction intensity, important aspects for the design of future systems. Players of Table Tennis for Three reported that the game facilitated enjoyment and that they engaged in the gameplay with their partners despite the geographical distance. The focus on the physical world during the design process appeared to facilitate the positive responses of the participants, however, further evaluation work is needed to fully assess the impact mixed reality systems that aim to support exertion have on their users.

We hope the presented investigation can contribute to an understanding of mixed reality systems, in particular in the context of gaming where supporting bodily movements are believed to facilitate more emotional and more physically demanding experiences. Such an understanding can help create physical, mental and social benefits; in particular an increase in fitness levels is currently often discussed in light of the obesity issue. It is believed that by delivering fitness benefits through gameplay, a wider audience could be reached. However, this does not mean that the exploration of a body-centric approach to mixed reality applications is limited to gaming applications. Future work will show if lessons learned from a game perspective can also be applied in other application domains, such as learning, training and maintenance.

Mixed reality systems have come a long way in their short existence, and their potential to enhance human's everyday life through offering novel interaction experiences is manifold. The combination of the benefits of the physical world with the advantages of virtual augmentation holds a promise for many new applications yet to come. The body plays a central role in how humans experience their physical environment and embodied others, and by considering this body and its potential for movement in such mixed reality interactions, exciting new experiences can emerge that can contribute to the well-being of its users. With our work, we hope we have added towards an understanding how this future could evolve and how it could be shaped, and inspired an exciting outlook on the role of exertion in mixed reality systems.

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