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Assessing the Influence of Passive Haptics on User Perception of Physical Properties in Virtual Reality

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Abstract. This paper presents a pilot study that explores the role of low-cost passive haptics on how users perceive physical properties such as the size and weight of objects within virtual reality environments. An A/B-type study was conducted as an air hockey simulation in which participants experienced two versions: one adhered to conventional VR settings, while the other incorporated a tangible surface, a real table. Statistical analysis of the data collected from post-study questionnaires indicated a shift in perception of size and weight when exposed to the haptic-enhanced simulation, with virtual objects perceived as larger or heavier. It was also noted that the observed shift of the user perception was stronger when the simulation with the tangible surface was experienced first. The paper presents details on the implementation of the air hockey simulation and the setup within the testing environment as well as the statistical analysis performed on the collected data, offering practical recommendations for future applications.

Keywords: Virtual Reality · Tactile and haptic interaction · Passive Haptics · User Perception

1 Introduction

Virtual reality (VR) has revolutionized the way we interact with digital environments, but achieving a truly immersive experience still poses challenges, particularly in replicating physical sensations. Various hardware solutions have been proposed such as electric muscle simulation [5] however the cost and setup implications of such interfaces are usually prohibitive for public use as mainstream hardware devices. Several studies have recently experimented the use of low-cost tangible objects within virtual environments [2, 3], and it has been shown to influence the user experience in various ways [8, 1, 6, 7, 4, 12]. Results from our previous studies indicated that the use of passive haptics contributes to an increase in the perceived level of enjoyment and realism [3].

This paper explores the impact of integrating low-cost passive haptic feedback into virtual environments on users' perception of size and weight. The focal point of this work is a pilot study conducted within the context of an air hockey simulation, utilizing a real-time tracked physical table (Fig. 1). The experimental design involved a randomized A-B testing sequence, wherein participants were exposed to two versions of the simulation. One version adhered to conventional VR settings, devoid of any passive haptic elements, while the other incorporated a tangible surface of interaction, i.e. a real table that served as the virtual air hockey table. Post-study questionnaires were administered to gather insights into participants' possible change of perception.

Fig. 1. Illustration of the experimental setup with a physical table. Components of the virtual environment are superimposed to show the alignment between the virtual and the real world.

The results yielded findings regarding the influence of passive haptic feedback on the perceived physical attributes of objects within the virtual environment. Participants consistently reported a notable shift in their perception of size and weight of the critical objects of interaction when exposed to the haptic-enhanced version of the simulation. Statistical analysis of the results that are presented in Sec. 4 indicate statistically significant differences between the two conditions. Participants consistently rated virtual objects within the haptic-enhanced simulation as larger or heavier compared to their counterparts in the conventional VR environment. More specifically, the virtual puck was perceived as heavier when the physical table was present. Furthermore, the 3D model of the air hockey table was perceived as smaller when the physical table was absent. These findings indicate that there is an impact of passive haptics on users' perceptual experiences, even with respect to the virtual (non-physical) objects within the simulation environment. This reaffirms and extends the observations from experiments presented recently in literature [11, 9]. Our results also indicated that the order of experiencing A and B versions of the simulation had an additional influence on the user's perception. In particular, the effects of the passive haptics were more intense when the simulation with the tangible objects were experienced first.1

The paper is organized as follows: Section 2 presents details of the development of the VR air hockey simulation with passive haptic feedback. Section 3 describes the study protocol and the user's demographics. Section 4 presents the results and the corresponding statistical findings.

Fig. 2. Screen capture of the virtual reality environment that was developed for the needs of this study.

2 Methods

A VR application was developed to simulate the tabletop game known as air hockey (see Fig. 1). In the real air hockey game, the center of interaction is a low-friction table, powered by air pressure, on top of which a circular puck slides when struck by the strikers held by the players. In front of the two opposing players, who stand on opposite sides of the table, there are two openings where players attempt to shoot the puck in order to score points. The sides around the table are slightly elevated to prevent the puck from falling off and can even be incorporated into the game by deliberately angling the puck off the side rail to change its trajectory and send it back towards the opponent's goal—a move known as a "bank shot".

A virtual air hockey simulation was created and deployed on Oculus Quest headsets using Unity 3D. The simulation featured a complete 3D surrounding environment themed as an unfinished basement, with a full-size air hockey table positioned in the center (see Fig.2). At the beginning of the application, users had the option to calibrate the virtual air hockey table to a physical table using pass-through view. During this calibration step, users could intuitively set the position and orientation of the virtual table by placing the two Oculus Quest controllers upside down on the real table. The midpoint between the controllers determined the location of the virtual table, while the vector between them defined the table's orientation on the X-Z plane. This interaction constrained the user's degrees of freedom to ensure that the virtual table was properly leveled and parallel to the floor, with a fixed size of 55" in width, which is typical for an air hockey table.

Fig. 3. Picture of the VR controllers with a 3D printed attachment and soft padding so that they can be used as air-hockey strikers on top of a physical table.

For the haptic version of this application, a physical table 55 inches wide or wider was required, such as a desktop, coffee table, workbench, or similar flat surface that was also clear of objects. In our testing environment, we used a classroom table that was 72 inches wide. The length of the table was generally not a concern, as the range of the user's motion is naturally restricted to the area in front of the user, covering the depth that the user can reach with stretched arms. The alignment of the virtual table with the physical table produced natural passive haptic feedback when touching the virtual table and allowed for natural interaction with it, such as leaning on the table to reach the puck.

To further improve passive haptic feedback and create seamless user interaction, the two VR controllers were used as strikers by placing them upside down and sliding them on the surface of the table, mimicking real air hockey strikers. The VR controllers were enhanced with a 3D printed attachment that could fit inside the tracking band of each controller and had a soft adhesive circular pad attached to it to protect both the table and the controllers from wear and tear due to prolonged friction (see Fig. 3). The soft padding also facilitated smoother sliding of the controllers on the table, further enhancing the interaction. Overall, the combined use of the table and the controllers as strikers resulted in an enhanced virtual environment where the two major objects of interaction provided passive haptic feedback. In the absence of a real table, the interaction is reduced to conventional VR user interaction, where the table is purely virtual and the user moves the controllers in the air. This conventional setup of our environment was considered the control case in our experiments, while the haptic setup was the test case.

It is worth mentioning that the only other object involved, even indirectly, in user interaction is the puck, which in both environmental setups is virtual. In real-world air hockey, although users do not directly hold the puck during play, they feel its presence through the force it generates when struck by the strikers. In our VR application, while we could not generate forces of such magnitude, we triggered the vibratory motors of the VR controllers each time they collided with the puck. This active haptic feedback served as a cue that enhanced user interaction with the virtual puck in both forms of simulation.

The developed VR application included other features such as a table-top user interface (UI) with options that could be time-triggered by placing a VR controller on them, moving barriers in the middle of the table to add a video game flavor to the traditional air hockey game, a scoreboard, sound effects, animations, and a multiplayer networking setup that enabled two remote players to play together on opposite sides of a shared virtual table. A video demo of the VR air hockey environment is available at [10].

3 User Study

A pilot study was designed to investigate how the presence of passive haptics (in our case, the table) within the VR simulation affects the users' perception of the physical properties of the main objects of interaction in virtual reality.

The study was designed as a randomized controlled trial (RCT) with a crossover design. In this design, each participant experienced both the test condition (VR with passive haptics) and the control condition (conventional VR) in a randomized order. This form of study helps to minimize the influence of individual differences and other potential sources of bias, allowing for a more robust assessment of the intervention's effectiveness.

The study was approved by the University of Florida institutional review board (IRB protocol 17378, approval date: February 8, 2023). In the study we enrolled 13 individuals in the period between February 27, 2023 and April 12, 2023 from the university's community. The age of the subjects ranged from 18 to 34, with a specific breakdown of 18 to 24 (N=8) and 25 to 34 (N=5). The majority of the subjects reported having used VR a few times prior to this study (N=9), while only a few reported using VR often (N=4). The level of prior air hockey experience varied among the subjects, with some having no prior experience (N=4), others having limited experience (N=5), and some being more experienced players (N=5).

The study began with participants responding to a series of demographic questions to collect information about their background and prior knowledge. Subsequently, participants underwent their first virtual reality experience, which involved playing a set of air hockey in single-player mode. The specific VR setup for this initial experience was randomly selected between the control and test conditions. Following this initial VR experience, participants answered a set of multiple-choice questions aimed at capturing their perceptions and impressions. The questions were in the form of statements such as "The puck was heavier than expected", "The puck was lighter than expected", etc. with the following possible responses: strongly agree, somewhat agree, neither agree or disagree, somewhat disagree, strongly disagree.

Next, participants engaged in the other VR experience, similar to the first, and subsequently provided feedback through the same set of questions. Finally, the study concluded with participants responding to a series of closing questions designed to gather additional feedback. These questions included a series of comparative multiple-choice questions with a 5-point scale and allowed participants to provide any other reflections they may have had after completing both VR experiences. Examples of questions included in the post-study questionnaire included: "In which experience did you feel that the puck was heavier?", "In which experience did you feel that the strikers were heavier?", etc. with the following possible answers: clearly the first, somewhat the first, about the same, somewhat the second, clearly the second. Because the first and second experiences were randomly chosen between the control and test conditions, the responses were normalized after the end of data collection. This was achieved by mapping the responses to the control and test cases accordingly, based on which experience was first and which one was second.

This sequential randomized controlled trial study protocol allowed for a structured examination of participants' experiences and perceptions across the two VR sessions.

4 Results

Due to the pilot nature of this study and the small number of participants, the results from the analysis of the collected data are not conclusive but their role is mostly indicative. The data were analyzed using Chi-squared test statistics or Fisher's exact test when the assumptions of the former could not be met. The presence of five possible choices in each question led to small expected frequency counts in some cells of the corresponding contingency tables, violating one of the assumptions of the Chi-squared test. To address this issue, we grouped responses into broader categories, such as combining 'weak' and 'strong' acceptance.

Table 1. Results from post-condition questionnaires

Metric	χ^2	p	**Direction**
Strikers heavier than expected	1.2	NS	Test
Strikers lighter than expected	3.84	<0.05	Control
Puck heavier than expected	2.25	NS	Test
Puck lighter than expected	0.26	NS	N/A
Table larger than expected	0.65	NS	N/A
Table smaller than expected	3.47	<0.10	Control
Table lighter than expected	3.91	<0.05	Control
Table heavier than expected	0.68	NS	N/A
User interaction smoother	4.24	<0.05	Control

Table 1 summarizes the results from the questionnaires completed immediately after each VR experience. For each question, we formulated a null hypothesis (H0), such as "there is no difference in the perceived weight of the strikers between the Control (traditional VR) and Test (VR with haptics) conditions", and an alternative hypothesis (H1), such as "there is a difference in the perceived weight of the strikers between the Control and Test conditions". When the χ^2 value corresponds to a significance level with a small enough p-value, the observed difference between the two conditions is statistically significant, leading to the rejection of the null hypothesis. This suggests evidence of a significant difference in user perception between the Control and Test conditions.

According to the results in Table 1, users felt that the strikers were lighter in the traditional VR experience (control case). A possible explanation for this result is that in the passive haptic VR experience, there is friction between the table and the sliding strikers (VR controllers), which may result in the perception that the strikers are heavier compared to the traditional VR experience in which they feel much lighter. Similarly, the table was perceived smaller and lighter in the traditional VR case, which corresponded to the feeling that the user interaction was smoother. Finally, although not statistically significant enough, the puck was perceived heavier than expected when the haptic table was present. This can be explained by the fact that all other major objects of interaction are tangible and this unconsciously is transferred to the puck, which is also perceived tangible or at least heavier.

Table 2. Results from post-test comparative questionnaire

Metric	Haptic VR
Felt like real air hockey	96.16%
Felt like real strikers	96.16%
Felt more immersive	84.61%
The physical table helped puck interaction	80.76%
Strikers felt heavier	76.96%
Puck felt heavier	69.23%

Table 2 shows results from the comparative questionnaire administered at the end of the session. Based on these results, the VR experience with passive haptics felt more like real air hockey and with real strikers. Furthermore, the environment felt more immersive, and the presence of the table facilitated puck interaction. Finally, both the strikers and the puck felt heavier, which aligns with the observations from Table 1.

Table 3. Assessing the role of the order of experiences

Metric	χ^2	p
First experience was more comfortable	4.46	<0.05
Felt more sick in second experience	3.00	<0.10
Puck feels heavier on table when test case is first	7.00	<0.05
Table feels larger when test case is first	3.80	<0.10

Finally, we analyzed the data to assess if the order of experience has any effect on the results. Based on the data shown in Table 3, the first experience was more comfortable, while the second experience was more likely to make the subjects feel discomfort. This finding is not surprising because users naturally get tired after some time in VR, particularly when engaging in physically intense interactions. However, it is interesting to note that the puck is perceived as heavier and the table as larger (as seen previously in Table 1), and this difference in perception is more pronounced when the test case (VR with passive haptics) is experienced first.

5 Conclusions

In conclusion, the pilot study presented in this paper underscores the significant influence of low-cost passive haptics on users' perception of physical attributes within virtual reality. By integrating tangible surfaces into VR environments, in our case an air hockey simulation, participants demonstrated a notable shift in their perception of size and weight. The results also indicated that prior experiences within such hybrid simulations influence the user's perception in conventional VR simulations that will be experienced afterwards primarily due to a possible shift in their expectations. These findings highlight the potential of passive haptic feedback to enhance immersion and realism in VR experiences. Moving forward, further research is warranted to delve deeper into the mechanisms driving these perceptual shifts and to explore optimal integration strategies for passive haptic feedback in diverse VR applications.

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