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Investigating how interaction with physical objects within virtual environments affects knowledge acquisition and recall

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Abstract. This paper introduces a small-scale study that examines the utilization of a simple physical object as the primary interactive tool in a gamified educational virtual reality (VR) application. The study aims to evaluate the impact of passive haptics on the learning process within VR environments. The findings suggest that incorporating passive haptic interfaces in VR has the potential to enhance the learning experience and overall outcomes. Specifically, the results indicate that participants exhibited increased confidence when using a physical object (a jar) rather than traditional VR controllers. This confidence led to more accurate interactions, such as pouring liquids, and contributed to an enhanced sense of immersion. Additionally, results from recall tests suggest that participants demonstrated improved memory retention when knowledge was acquired through the haptic VR experience.

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

1 Introduction

The use of passive haptics in virtual reality (VR) environments has been shown to improve procedural learning across various application domains such as first responders training, kayaking, and others [4, 3]. Studies have shown that introducing haptic interfaces in VR can positively affect user experience [1], enhance simulations [7, 8], and improve performance in various forms of training [5, 4], ranging from medical procedures [6], to music conducting training [2].

In this paper we want to go one step further and quantify the effect of passive haptics on knowledge acquisition and recall, extending our laboratory's previous research projects on the use of low-cost passive haptics in VR [2, 3]. We developed a specialized virtual reality application for learning various chemical compounds and their components. Participants engaged in activities that involved precise mixing and proportioning of chemical components to form targeted compounds (see Figure 1). Employing an A-B test framework, participants were randomly

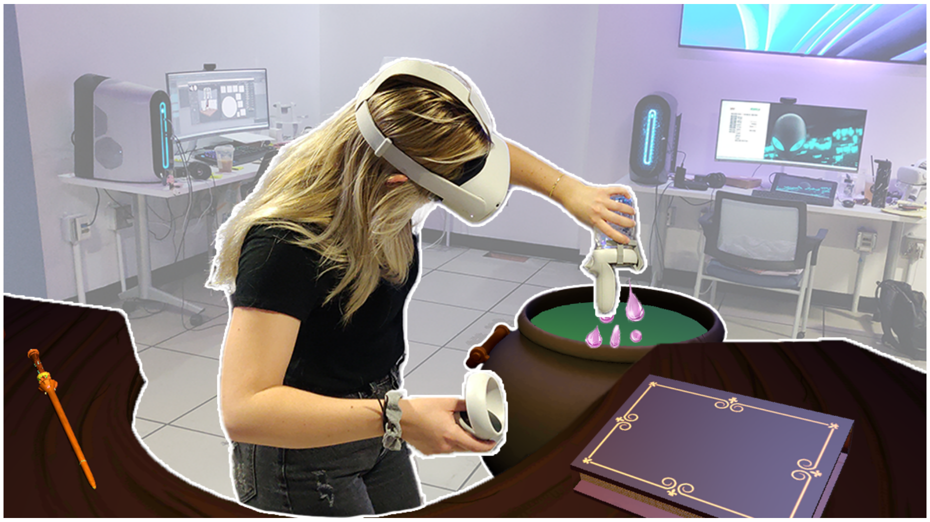

Fig. 1. Illustration of the user interaction using the physical jar. Components of the virtual environment are superimposed to show the alignment between the virtual and the real world.

assigned to two identical virtual reality environments, differing only in the substitution of the VR controller with a physical jar.

Pre- and post-study surveys were administered to gauge user perceptions regarding interaction accuracy and realism, as well as their ability to recall acquired knowledge (specifically, the list of components) from their virtual experience. Statistical analyses, including chi-square tests, were performed on the collected data, with detailed results outlined in this paper.

Two key findings emerged from the study: (a) the presence of the physical jar significantly heightened perceived interaction accuracy, particularly in precise liquid pouring tasks, and (b) users exhibited improvement in knowledge recall when the knowledge was acquired using the physical jar as opposed to a conventional VR controller. These results establish a compelling correlation between the integration of passive haptic objects in VR and knowledge acquisition and recall. Despite the study's small size, which limits the conclusiveness of the results, the findings clearly indicate that the use of passive haptic interfaces in VR can improve the learning experience and outcomes, and this project lays the groundwork for a larger-scale research study in the future.

The rest of the paper is organized as follows: Section 2 describes the VR application that was developed for the purposes of this study, Sec. 3 presents the details of the user study protocol, and Sec. 4 discusses in detail the results collected from the pilot study.

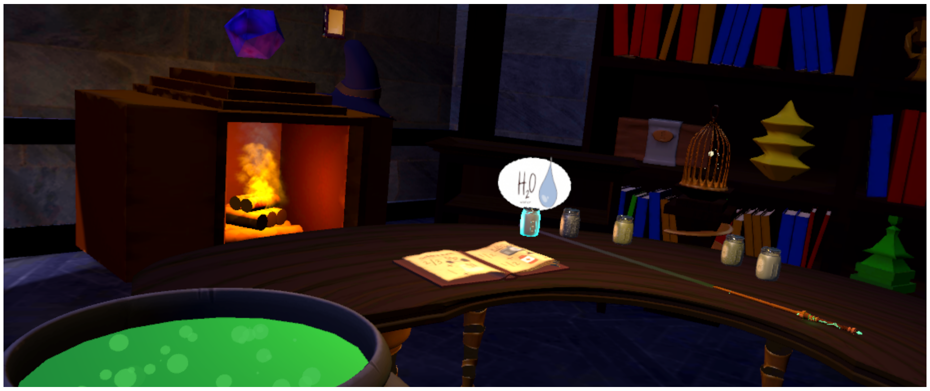

Fig. 2. Screen capture of the virtual environment showing the jars with the constituents (right), the recipe book (center), and the mixing cauldron (left).

2 Methods

A novel virtual reality application for Oculus Quest 2 headset was developed in Unity 3D for the needs of this project. The purpose of this application was to simulate a small-scale training process, during which the users obtain new procedural knowledge. More specifically, in this virtual experience the users had to complete a series of procedural tasks that involved mixing various components to create six specific compounds: Aluminum Iodine (3 constituents), Caesium (2 constituents), Thermite (2 constituents), Golden Rain (4 constituents), Luminol (4 constituents), and Belousov (6 constituents). The process was gamified by representing all constituents as liquids that had to be poured in the right quantities into a cauldron and mixed together to create the compound. For example, to create thermite the users had to mix together two constituents: aluminum and iron oxide (rust). A recipe book that appeared in front of the users provided the list of the constituents and the appropriate quantities for each compound. Figure 2, shows a screen captured view of the developed gamified application.

The main object of interaction was a jar that the user was holding continuously throughout the virtual experience. The content of the jar could change interactively into one of the available constituents from each recipe. To facilitate testing the main hypothesis of our project, a passive haptic version of the jar was designed using a real jar that was half filled with water. One of the VR controllers was rigidly attached to the jar using a 3D printed attachment as shown in Fig. 3, so that the jar is tracked in real time. The other VR controller was normally held on the other hand (as shown in Fig. 1), and was used for typical user interactions, such as making selections in VR, and was visualized in VR as a wand to match with the rest of the gamification elements.

The same VR application but without a physical jar was used as the control case. In that version, the user was holding the VR controller instead of the real jar, but it was visualized as a virtual jar identical to the one shown in the test

Fig. 3. Picture of the haptic jar with the VR controller using a 3D printed attachment.

case version. Therefore, the only difference between the test and control versions was the presence or absence of the physical jar respectively, which was the only variable in our study.

3 User Study

A pilot study was designed to investigate how the use of passive haptics in educational VR applications could affect learning outcomes. Starting with this broad topic in mind, a small-scale experiment was designed using the generalizable VR application that was presented in Sec. 2. More specifically, the VR application was used as a training platform that exposed users to new knowledge through an interactive experiential learning session.

The research study was structured as a randomized controlled trial (RCT) employing a crossover design. Within this framework, every participant underwent both the test condition (real jar version) and the control condition (traditional VR controller version), with the sequence randomly determined. This methodology aims to reduce the impact of individual variations and potential biases, enabling a more comprehensive evaluation of the intervention's efficacy, within the limits of the pilot nature of our study.

The study was approved by the University of Florida institutional review board (IRB protocol 17379, approval date: February 8, 2023). A total of 12 individuals participated in this study in the period between February 27, 2023 and April 19, 2023. The subjects' ages ranged from 18 to 34, with eight falling into the 18 to 24 age group and four into the 25 to 34 category. Among the participants, six had used VR a few times before the study, while three reported using VR frequently, and another three had never used VR prior to the study. None of the subjects were familiar with the specific training content of the VR application, ensuring equal exposure to new knowledge for all participants during the study.

In the beginning of the study session, the order of the two experiences (test and control) was randomly chosen. The session started with a pre-test questionnaire covering demographics questions, followed by the first VR experience. After that, a post-test questionnaire was administered with multiple choice questions about the first VR experience. The questions were expressed in the form of statements such as "It was easy to pour precise liquid amounts" with five possible answers ranging from "strongly agree" to "strongly disagree". Then, the subject had the second VR experience followed by another post-test questionnaire with the same set of questions as before. The session concluded with an exit survey that included A-B questions comparing the two experiences, a recall test assessing the acquired knowledge, and other open-ended feedback questions.

4 Results

As this study was conducted in a pilot capacity with a small participant pool, the conclusions drawn from the data analysis are largely suggestive rather than conclusive. Data analysis employed Chi-squared test statistics or Fisher's exact test in instances where the former's assumptions were not satisfied. Furthermore, to address the issue of low expected frequency counts in the corresponding contingency tables, the responses were grouped into broader categories, by merging 'weak' and 'strong' agreement or disagreement levels accordingly.

Table 1. Results from post-condition questionnaires

Scale	χ^2	p	**Direction**
Jar was lighter than expected	15.5	<0.001	Control
Jar was heavier than expected	12.0	<0.001	Test
Wand was lighter than expected	0.2	NS	N/A
Wand was heavier than expected	1.7	NS	N/A
Felt the liquid inside the jar	11.0	<0.001	Test
Jar was intuitive to use	2.2	NS	N/A
Easy to pour precise amounts	4.9	<0.05	Control

Table 1 presents the analysis of the data collected from the two post-test surveys. Each statement in the survey was assessed using a set of two complementary hypotheses: the null hypothesis stating no perceived difference between the two conditions (haptic VR vs. traditional VR), and an alternative hypothesis suggesting a difference. When the statistical test yielded a small p-value, indicating significance, the null hypothesis was rejected, which implied evidence of a significant difference between the two conditions. For example the virtual wand, which was operated by a VR controller in both VR experiences, was not perceived differently (lighter or heavier) across the two VR experiences. This is indicated by a low χ^2 value, which corresponds to a non-significant (NS) finding in Table 1. Statistical significance was found regarding the perception of the jar across the two VR experiences: it was perceived as lighter than expected in the control case and heavier than expected in the test case. Similarly, users were able to feel the liquid inside the jar in the test case, as anticipated. One of the most intriguing statistically significant findings reported in Table 1 is that users found it easier to pour liquids in precise amounts in the test case (real jar) compared to the control case (VR controller).

Table 2. Results from post-test comparative questionnaire

Scale	%
Was more immersive	91.66%
Was more appropriate	77.27%
Teaches how to judge measurements	70.83%
Was more enjoyable	66.66%
Was clear how to operate	66.66%
Easier to remember ingredients	62.50%
I felt dizzier or nauseated	54.16%

Table 2 summarizes the results from the A-B comparative questions included in the exit survey. To avoid any confusion with the order of the two VR experiences, all responses in this table are reported with respect to the test case (real jar). According to the collected data, the users felt that the haptic VR experience was more immersive, more appropriate for this type of interaction, and that it better taught how to judge measurements, which is in agreement with the last statistically significant finding reported in Table 1. Furthermore, nearly two-thirds of the subjects found the VR experience with the real jar more enjoyable, clearer to operate, and easier to remember the ingredients.

Finally, Table 3 presents the results from the recall test administered as part of the exit survey. The table compares the results based on the first experience (control or test case). For example, Aluminum Iodine was presented in this gamified experience as the result of a reaction between three components. Recall was measured using the formula $recall = n_{present} - n_{absent}$, which counts how many of the correct components were identified by the subject minus the number of components missing from their response. In the previous example, the maximum possible score was 3 if all three components were correctly identified, and the smallest possible score was -3 if none of the components were identified. According to the first row of Table 3, subjects who started with the control experience (VR controller) identified, on average, 1 out of the 3 components, while subjects

Table 3. Results from the recall test

Compound	Components	Control Recall	Test Recall	Δ Recall	%
Aluminum Iodine	3	1.00	2.00	1.00	33.3%
Caesium	2	-0.40	0.33	0.73	36.6%
Thermite	2	-0.80	-0.83	-0.03	-1.6%
Golden Rain	4	0.80	1.50	0.70	17.5%
Luminol	4	1.20	2.16	0.96	24.1%
Belousov	6	0.00	4.00	4.00	66.6%
Mean	3.5	0.30	1.52	1.22	29.4%
Median	3.5	0.40	1.75	0.85	28.7%
Std. Dev.	1.5	0.81	1.65	1.40	22.7%

who had the test experience first (real jar) identified, on average, 2 out of three components, representing a 33.3% increase.

By observing the mean and median differences, it is evident that participants who acquired the knowledge with the real jar in their first experience demonstrated approximately 29% better recall than those who acquired the knowledge with the conventional VR experience. This finding indicates that the presence of passive haptics in virtual reality can positively affect knowledge acquisition and recall. Furthermore, it suggests that the modality (haptic or conventional VR) of the first experience during which new knowledge is acquired plays a significant role.

5 Conclusions

In conclusion, this paper presented a small-scale study that employed a simple physical object as the primary interaction tool in a gamified educational VR application. The study aimed to evaluate the impact of passive haptics on the learning process in virtual reality. The findings revealed that participants exhibited greater confidence when operating the physical tool (in our case, a jar), enabling them to pour liquids more accurately and enhancing their overall sense of immersion. Additionally, recall tests indicated that participants demonstrated improved memory retention when knowledge was acquired through the haptic VR experience initially. While the study's small size limits the conclusiveness of the results, they clearly suggest that the incorporation of passive haptic interfaces in VR can significantly enhance the learning experience and outcomes in various ways.

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