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Prof.a Dr.a Carla Denise Castanho (Orientadora)
CIC/UnB

Prof. Dr. Tiago Barros Pontes e Silva
DIN/UnB

Prof. Dr. Mauricio Miranda Sarmet
IFPB

Prof. Dr. Marcelo Grandi Mandelli
Coordenador do Bacharelado em Ciência da Computação

Brasília, 20 de Maio de 2021

The resilience of body ownership illusion in a virtual reality environment amidst visual-tactile asynchronies

1st Daniel Marcos Botelho Barbosa
Depto. de Ciência da Computação
Universidade de Brasília
Brasília, Brazil
wisebdan@gmail.com

2nd Carla Denise Castanho
Depto. de Ciência da Computação
Universidade de Brasília
Brasília, Brazil
carlacastanho@unb.br

***Abstract*—To guarantee a good experience in virtual reality is of interest to both industry and the scientific community. That made the interest in understanding the body ownership illusion increase. This research evaluates two types of visual-tactile asynchronies to better understand the limits of the illusion. First, a virtual environment was designed to induce the volunteers into the illusion. Following that, some visual-tactile asynchronies were inserted throughout the experiment. The majority of volunteers did not report any interruption of the illusion where it was expected to happen, i.e., where asynchronies were purposefully added in a try to break the illusion. Analyzing the data collected, it was possible to conclude that the body ownership illusion is stronger than anticipated. It is so strong, in fact, that it is conjectured that there is some sort of alternative rationalization happening in the volunteers' minds to make sense of the mismatches between the expected sensory inputs and the actual ones. Or, at least, something similar to this effect.**

***Index Terms*—body ownership, virtual reality, illusion, experiment**

I. Introduction

Although virtual reality technology has been around for a few decades [1], [2], it has gained notoriety and significant growth since 2016 [3]. This technology is commonly associated with games, however, its use goes far beyond that [4]–[7]. The level of immersion it offers makes it interesting for many different uses [8], [9]. Psychological therapies, education, architectural projects, medical and military training, and even medical and physical therapy treatments, for example, make great use of virtual reality [4]–[6], [10].

The human brain is susceptible to different types of illusion and, with the immersion proposed by virtual reality, one of the strongest and most common illusions is the illusion of body ownership [11], [12], which is the sense that the virtual body, in this case, is your own body, or at least part of it [13], [14].

Much of the research on the illusion of bodily property that has been done in recent times, both in the fields of psychology and technology, is aimed at understanding the minimum conditions necessary for the phenomenon to occur or to increase its intensity [15]–[18]. However, understanding the interruption point of the illusion is necessary to avoid situations that could cause this interruption at unwanted times. Therefore, the study of this phenomenon contributes to the development of virtual environments that make use of illusion.

Once the illusion is happening, it is necessary to be cautious so that there is good maintenance. For, it is not exactly known about the nature of the illusion with respect to its resilience [19]. That is, if the illusion is difficult to establish but easy to maintain, or if it is easy to establish but extremely volatile, or even some combination of these.

Visual-tactile synchrony (VT) is the synchrony between the visual stimulus of touch. In the case of this experiment, the synchrony between a VT stimulus in the virtual environment and the same touch stimulus in the real world. VT synchrony and visual-motor congruence (VM) are two of the main factors that contribute to the establishment of the illusion. Due to the fact that VT synchrony is one of the most important components for the establishment of the illusion of Body Ownership (BO) [20], it is thought that the breaking of expectations in this synchrony causes the interruption of the illusion in virtual reality environments (VR). However, it is perfectly possible that the requirements for maintaining the illusion are different from what is necessary for its establishment.

When it comes to the interruption of the illusion, there are several approaches to be studied in an infinite number of possible ways. Such as levels of immersion in illusion, varying levels of stress, focus, fear, VM congruence, etc. And even for each variation of this, there are infinite options to approach. Therefore, we decided to investigate whether the simple existence of VT asynchronies (expectation breaks) causes the interruption of the illusion, if so if this interruption is affected differently between the two asynchrony conditions: Primary-expectation Breaking (PB) and Secondary-expectation Breaking (SB).

The Primary-expectation Breaking (PB) has to do with primary care. It is the absence of touch in the actions that are the volunteer's goals, maintaining the visual stimulus. That is when performing some conscious action in which there is an expectation of tactile stimulation and this, in turn, is not felt. For example, if the volunteer places some part of the body in the path of a solid moving object in order to obstruct its passage and not feel the touch when the object meets its arm (or part of the body).

Secondary-expectation Breaking (SB) has to do with the background. It is the absence of touch in actions not related to the volunteer's objective, maintaining the visual stimulus. That is, it's something he expects to feel but isn't paying attention to. For example, if the volunteer is focused on doing some action and consciously, but not paying attention, some other object passes through his arm and perhaps he doesn't feel it.

In chapter 2 of this document we describe the entire experiment performed, as well as relevant details of the implementation of the experimental environment and the expected results. Chapter 3 is dedicated to reporting collected data, graphs, and information that may be relevant to the analysis. Chapter 4 describes the conclusions reached at the end of the study and possible approaches for future work.

II. Problem and Experiment

For this analysis, an experiment was carried out in which volunteers were invited to be inserted in a virtual reality environment. This experiment consists of performing tests with expectation breaks in order to make an initial investigation into the causes of the interruption of the BO illusion.

A. Ambiente Virtual

For this, a virtual environment was created in Unity3D[1] where each volunteer will be stimulated with synchronous visual signals of their real movements (VM) at all times and tactile signals congruent with the visual signals (VT synchrony) with the aim of inducing the illusion of full body ownership [11] with as much reliability as possible. Volunteers will be in this environment for a while to ensure the illusion is happening.

Before the volunteer undergoes VR, he was informed that the experiment consists of a test of BO illusion interruption and, with this, this concept was also briefly explained. In addition, for the control of interruptions, it was requested that, throughout the experiment, he be informed every time he realized that he left the illusion through some keyword. Likewise, it was explained how the controls work and their task within the virtual environment. Then, during the reception of the volunteer, Questionnaire 1 is presented for him to answer. This questionnaire has a consent form for the collection and use of physiological data, some demographic data questions, a 5-point Likert scale for the level of experience with VR, nervousness and insecurity.

The developed virtual environment was adapted and based on the tutorial made available for free by the online courses platform Udacity[2]. It consists of a room in an apartment in which the volunteer will be seated in a chair in front of a coffee table and with control in their hands. There's an open window in front of you that lets in a wind (this touch stimulus was performed in the real world) and an interactive TV nearby, which will guide the entire experience through floating screens. There are also several objects that make the environment more alive, such as a radio playing music, a clock ticking, among others.

The objective of the experience, for the volunteer, is simply to explore the apartment's new technologies according to the automated instructions provided by the interactive television. One of these technologies is a psychophysiological signal measuring box in which there is a ball that comes out of it and performs vertical touches. The television instructs the volunteer to place their arm over the ball to feel the touches and count them, making this activity their primary attention. At the same time, there is a drone with one hanging ribbon that walks around the environment carrying out inspections. The drone was programmed to go through where the volunteer's arm should be when counting the ball hits so that the tape touches his arm. In this way, the tapping of the tape becomes the background, as he knows that the visual-tactile stimulus must happen, but he is not paying attention.

Thirty-three volunteers were selected to participate in the experiment. Each volunteer was assigned to a test group of the same size. Group 1 is the control group, in which expectations will not be broken intentionally during the entire experience. Group 2 is the group in which only PB will occur. And finally, Group 3 is the group in which only SB will purposely occur.

Initially, there is the acclimatization period, in which the volunteer gets used to the environment, and at the same time, the controls are explained. After all the explanations, a drone and box run are performed to test your understanding of your tasks. Then, he will answer Questionnaire 2 within the virtual environment that contains control questions to find out if the volunteer is under the effect of the illusion.

After completing Questionnaire 2, the testing phase begins, in which VT asynchronies are introduced according to each group at pre-defined times for approximately ten minutes. At the end of this period, Questionnaire 3 must be completed to complete the data collection. This questionnaire has the same questions as Questionnaire 2, plus a few more about why the volunteer reported interruptions and how he felt.

To assist the data analysis that is done after the experiments are carried out, a script called Logger was implemented. This script generates one file per run named in the format YYYY-MM-DD_N.csv (N being an integer greater than or equal to 0 representing the current run).

As soon as the Logger starts or ends, it records these moments. This script exposes only one function, called Log, which receives a string with what must be added to the log file. This function records what was requested along with a timestamp in the local time zone.

At various times, various scripts use this class to record important or potentially relevant information. These records were designed to facilitate data analysis and notice patterns in illusion interruptions to know if they were happening at the expected times, in addition to storing other possible relevant information.

[1]https://unity.com/pt

[2]https://classroom.udacity.com/courses/ud1014

B. Expected results

If VT expectation breaks do indeed cause interruptions to the illusion, Control Group 1 cannot report many interruptions to the illusion, almost no interruptions are expected. In addition, the reason there are no interruptions must be because the volunteers have always been in the illusion and not the other way around. In addition, Groups 2 and 3 must have a significantly higher number of interruptions than the Control Group.

Similarly, if the two types of breaks (PB and SB) affect the interruption of the illusion to different intensities, the number of interruptions reported in Group 2 must be different from the number of interruptions in Group 3.

III. Data and Results Analysis

A. Collected data

In total there were 33 participants, with 28 valid data at the end. The discarded data resulted from preliminary tests and that some volunteers did not understand their task perfectly and, therefore, did not experience it correctly. The experiment does not require prior knowledge or experience with the technology or the concepts covered, nor any specific age group. In addition to the researchers, the presence of only one volunteer at a time and without companions was allowed.

No one said being very familiar with VR or with the illusion of BO, only 3% reported relevant experience with VR, and 15% with BO, 6% alleged to have some experience with VR, and 3% with BO, 27% of volunteers pointed out little experience with VR and 15% with BO. Those reporting no familiarity with VR and the BO illusion were approximately 63.6% and 66.6% respectively, according to the graph below (Figure 1).

Among the volunteers, 14 are female (42.4%) and 19 are male (57.6%). In total, 22 had no level of nervousness (66.6%) and 26 no level of insecurity (78.78%), 8 people reported a low level of nervousness (24.2%), and 7 of insecurity (21.2%). Those with a medium level of nervousness add up to 3 (9%). For the medium insecurity, high and extreme levels of nervousness and insecurity, no number was counted (0%).

Regarding the age group of participants, the average age of volunteers is 27. The minimum age is 13 years and the maximum is 56 years old.

B. Data analysis

The data aggregated to these graphs contain the questions related to VM congruence (Figure **??**), VT synchrony, and some extra control questions.

These questions, which were asked only at the end of the entire experiment, are related to the interruptions in the illusion itself. These can range from questions about immersion to insight into what may have caused the interruption.

For a better understanding of the cause of the interruptions of the illusion, a comparison was made between the moments that were reported interruptions of the illusion by the volunteer and the moments in which this reportings was already expected.

In the graphic in Figure 2, "Should report" are points where an interruption was expected to occur but was not reported; "Reported wrong" are points where outages were not expected but were reported; and "Reported right" are points where an interruption was expected and in fact happened.

The table in Figure **??** shows the times when the interruptions of the illusion were reported and the times when there was a breach of expectation. The secondary VT stimuli are always at the same time as the primary ones and the QS are at times when the primary stimulus remains congruent and vice versa. As with the graphic in Figure 2, it is clearly noted the large presence of reportings at times when there was no break.

Through the Table in Figure **??**, it is possible to see that, for Group 1, in which there was PB, there was only 1 reporting of interruption of the illusion in a moment when it was not expected (test nº 11). However, there were several other times when PB was introduced, but volunteers reported no interruption of the illusion.

C. Results

Physiological data were collected from all volunteers during the experiment using the Empatica E4 device. According to M. Slater et al. [12], there are alterations in the individual's physiological signs under the effect of the BO illusion when threatened by some virtual object. However, the objective of this work is limited to analyzing the impacts of breaches in expectations. Therefore, this data was saved but not used.

a) Robustness of the Questionnaires: Before any further analysis, it should be considered that some answers to the questionnaires presented contradictions and inconsistencies. This is probably due to the fact that the volunteer did not fully understand their task, or the concepts, or the question that was asked, or the social desirability.

This behavior was observed in several volunteers throughout the testing phase. Several times the volunteers asked, during the experiment, what they should do and had doubts about what exactly they should report. However, regarding the distraction, it became clear when a volunteer started to answer the questionnaire incoherently, however, he realized his mistake and came back to change. In addition, a volunteer commented on the questionnaire that he felt distracted.

One possible explanation for this is that the illusion explanation may not have been enough. Or, the volunteer was distracted by the time he received this new information. Or, the amount and density of new information overwhelmed him, causing him not to fully understand what was asked.

At the end of each experiment, some volunteers made relevant comments regarding what is being studied. However, due to the form created, there was no field for several of these comments to be registered. For example, if a volunteer does not report any interruptions throughout the experiment, there were no fields for him to explain about why he thinks there was none, or just report how he felt. These comments were made informally and many of them were of great importance.

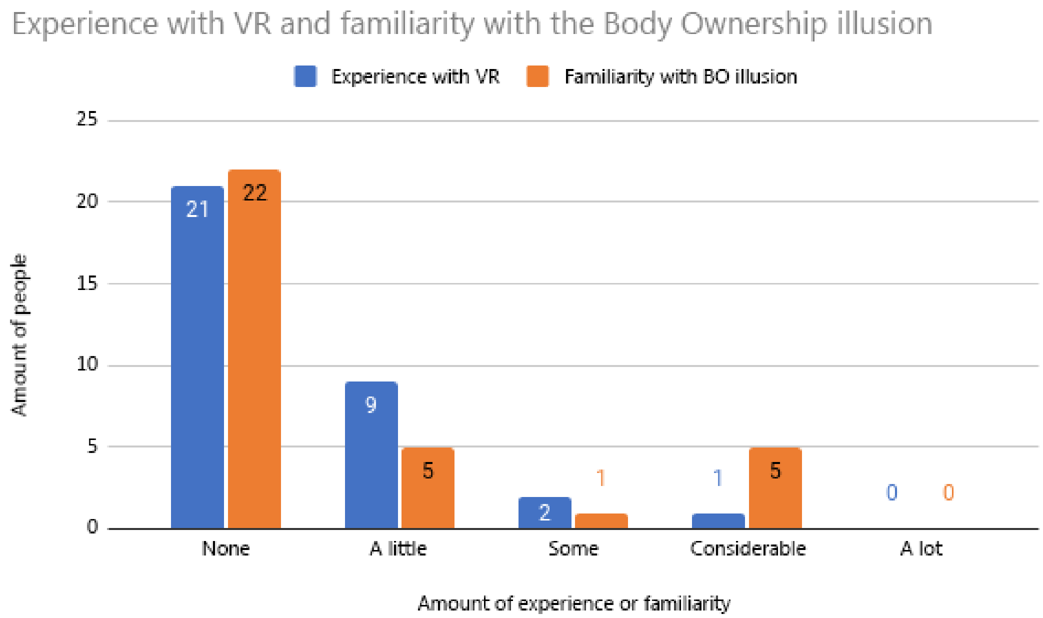

Fig. 1. Histogram of the volunteers' previous experience

b) VT Stimulus Synchrony: The difficulty of maintaining good VT synchrony detracted from the quality of the experiments. The volunteers with the highest number of undue breaks are in relation to the balls and, in general, people involved in music or with a good sense of rhythm. In this way, most of the real touches that were not perfectly synchronized with the touch in the virtual environment influenced the interruption of the illusion for that specific audience. The ideal is for the virtual environment to be synchronized with the real one, and it may be through a tracker on the object that makes the spatial translation for the virtual environment.

The number of reports in unexpected moments and the amount of comments in the final questionnaire about the asynchrony of the ball having hindered the experience showed that a good VT synchrony makes a difference for the resilience of the BO illusion.

Because of this, the data collected with Group 3 (SB) has an unwanted noise and is too big to draw any meaningful and reliable conclusions. In fact, looking at the graphs, it could be concluded that volunteers in this group had less stability of the illusion, with constant breaks caused by any incongruity and asynchrony.

c) PB Impact: The presence of PB, while partially disrupting the experience, didn't cause as much disruption to the illusion as expected. The interruptions of the illusion at the moments in which there was PB were reported as shown in the graphic in Figure 5, but these reports did not happen at all moments of PB.

If PB really affected the interruption of the BO illusion as expected, the number of interruptions of the illusion by the ball should be greater (Figure 5(a) should be the inverse of the observed) and the feeling that the hands virtual were the hands themselves should be harmed (Figure 5(c)). How much PBs affect experience (Figure 5(b)) is higher than all other groups. This means that even if there is a PB and the illusion still exists, it doesn't go unnoticed and spoils the experience and sense of presence (Figure 6).

d) Illusion Resilience: One of the recorded comments from one of the volunteers was:

> "Quando eu não sentia a bolinha, a ilusão não sumia. Eu percebia como se o objeto virtual se tornou imaterial, mas a mão continuava sendo minha. A diferença estava no objeto, não na minha mão."
>
> "When I didn't feel the ball, the illusion didn't disappear. I felt as if the virtual object has become immaterial, but the hand was still mine. The difference was in the object, not my hand."

- *Free translation*

When considering this comment, the previous point, the data obtained, and other similar comments, it is concluded that the illusion appears to be a robust phenomenon. Apparently, the illusion of BO in VR is resistant to expectation breaks to the point of conjecturing that there is a discarding or alternative rationalization of what is being experienced to deal with the discrepancy between the sensory stimuli received and the expected sensory stimuli. As, for example, in the case of this experiment, there was a rationalization that the virtual ball became intangible and that this was the interpretation desired by the researchers or by the virtual environment itself.

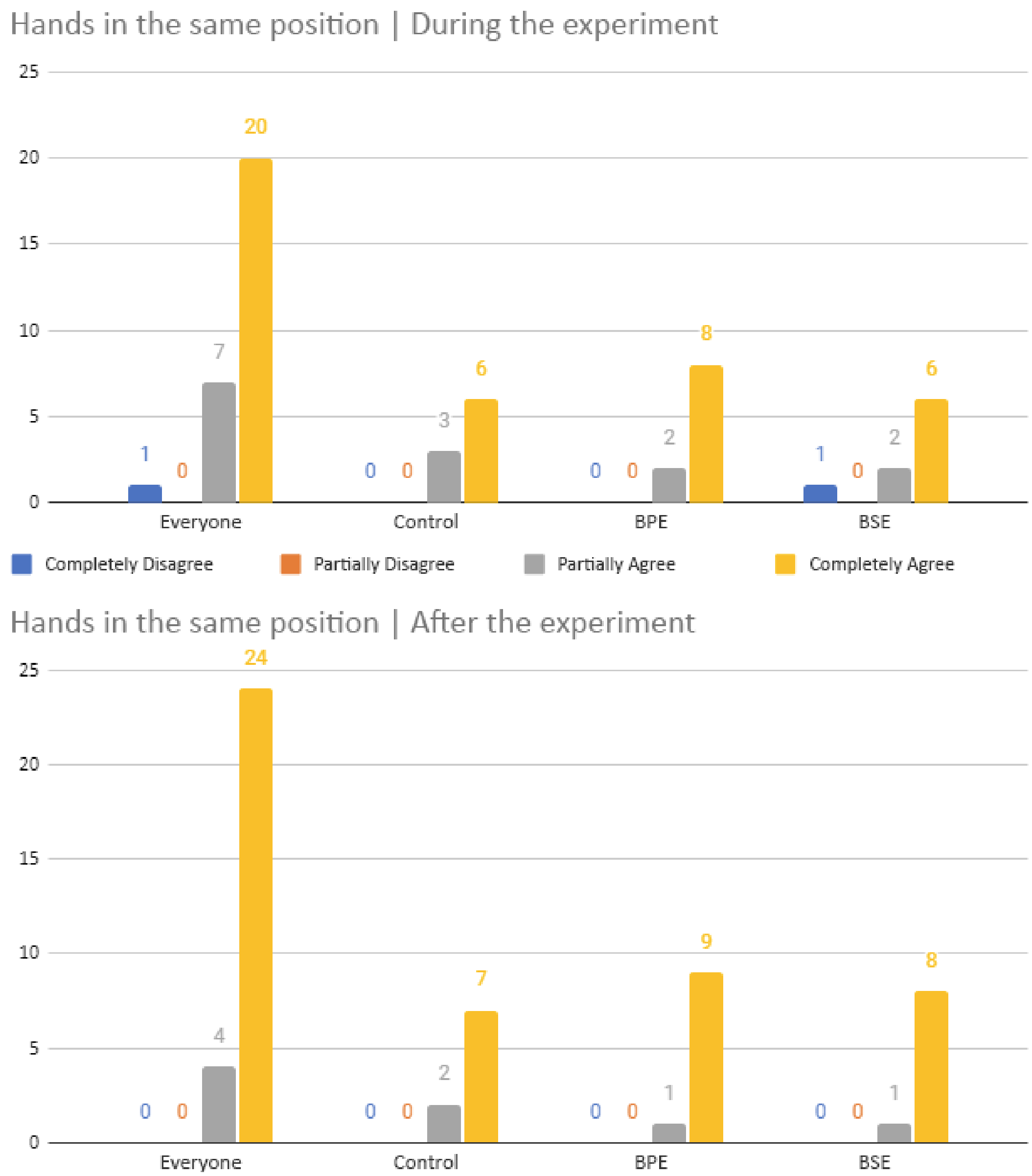

Fig. 2. Answers on the perception of congruence VM.

IV. Conclusions

To optimize the experience and results of therapies, treatments, and the many other uses of virtual reality, there needs to be a more consistent immersive experience. Thus, understanding the BO illusion's breakpoint is critical to avoid situations that could cause it to break during each of these situations. Therefore, this work tested, through an experiment, whether breaking the expectation of a real synchronous stimulus of touch causes the interruption of the illusion of bodily property in virtual reality environments and whether the nature of the breaking of expectation is relevant to the interruption of the illusion.

During the initial study of what it takes to interrupt the illusion of bodily ownership (BO) in virtual reality (VR) environment, behaviors that were quite different from what were expected were noted. Keeping visual-motor congruence (VM) constant and injecting punctual expectations breaks related to visual-tactile synchrony (VT), two specific types of breaks and their impact on the attempt to interrupt the illusion were evaluated.

After the entire process of data analysis, it is clear that the first situation analyzed was confirmed, unlike the second. However, although expectation breaks in VT sync cause the BO illusion to break, these breaks are not as significant as expected. In other words, the established illusion was resilient enough to withstand the breaks without being, in general, interrupted, validating what was concluded by M. Slater and A. Maselli [21], without the need to use a full-body avatar

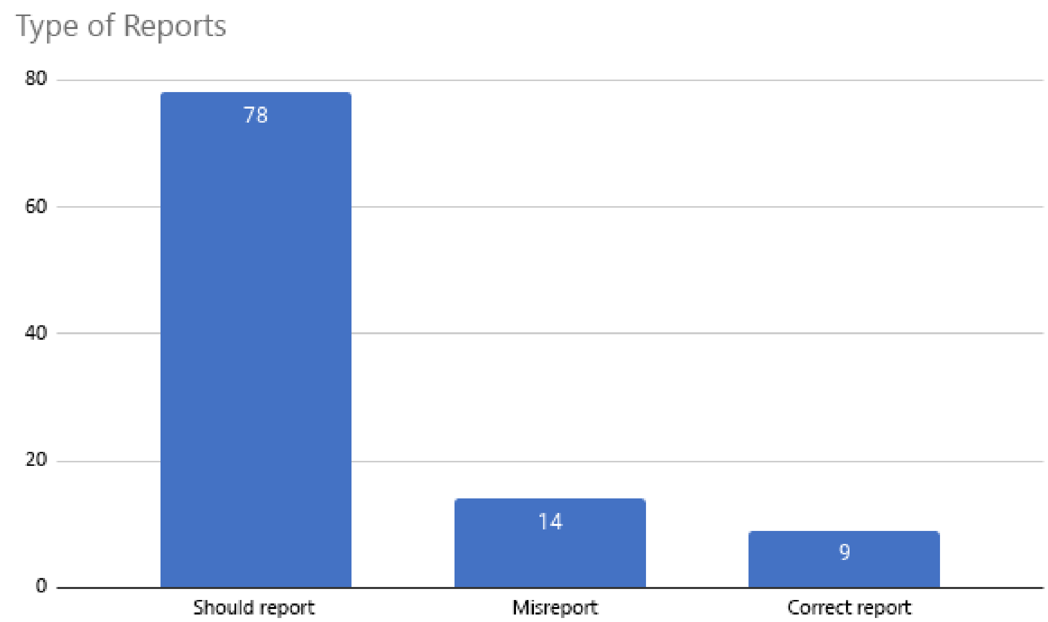

Fig. 3. Characteristics of the reportings found in the volunteer report.

Test	Event	Type of Event	Reports per group		
			BPE	BSE	Control
1	Crate	BPE			
2	Crate	Normal			
3	Crate	Normal			
4	Crate + Drone	Normal		1	
5	Crate	BPE			
6	Crate	BPE			
7	Crate	Normal			1
8	Crate + Drone	BSE			
9	Crate	Normal			
10	Crate	BPE	1	1	
11	Crate + Drone	Normal	1		
12	Crate	BPE		1	
13	Crate + Drone	BSE		1	
14	Crate + Drone	BSE		1	
15	Crate	BPE	2		

Fig. 4. The time when interruptions of the illusion were reported and time when there was a breach of expectation. Without outlier volunteer data.

like used in their experiment. This event demonstrates that the illusion can be more resilient than initially expected.

Even in the face of some harmful side effects to the results arising from the design of the experiment, it is possible to rule out VT asynchronies of the same nature as those tested in this research.

V. Future works

For the next experiment, a possible solution to overcome the problem of the volunteer not easily understanding their tasks, even with the intense repetition of instructions, a tutorial is suggested that guides the volunteer step by step, so that it is only possible to follow to the next step if the current one is completed correctly and reliably. Another resource that could also be used is visual guides in repeating instructions.

Additionally, a better architecture for the code that facilitates changing the timing of events and better synchronization, regardless of the volunteer's agility, would benefit the experiment by allowing a more iterative and simplified process for removing bugs.

As the illusion requires breaks in the expectation of visual-tactile and visual-motor stimuli, it is necessary to keep the volunteer susceptible to visual stimuli. Therefore, as some volunteers didn't bother to observe the ball touching their arm, a solution to keep the visual stimulus active is to make the element within the environment that stimulates touch come from above or from the sides, in order to avoid the occlusion of the object by the hand of the volunteer. Another solution would be to redesign the experiment taking into account this new information and knowledge about the observed behaviors of the volunteers.

Some possible approaches for future work are:

a) Using physiological data to try to predict interruptions: That is, analyzing whether there are patterns in these data and whether it is possible to know where interruptions in the illusion will occur without the volunteer reporting, only with the data collected.

b) Testing whether the interference of a different than expected touch affects the illusion: For example, analyzing whether a solid, solid object hits the user's virtual body, but the user feels a soft, gelatinous touch, for example, can

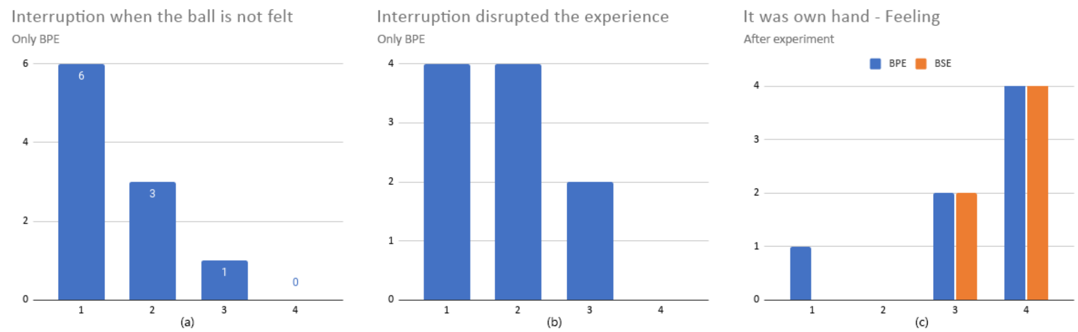

Fig. 5. Graphics that indicate low importance of PB for the interruption of the illusion

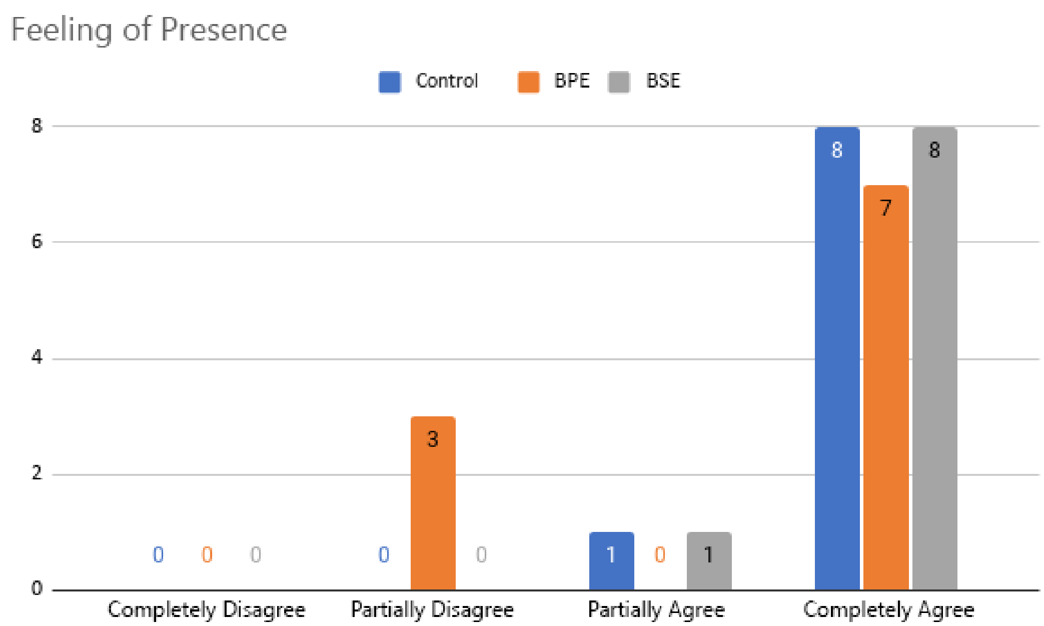

Fig. 6. Feeling of self-reported presence by the volunteers.

be considered asynchrony and evaluate whether it causes interruption of the illusion or not;

c) Investigate whether the frequency of sync breaks in any way affects the volatility of illusion maintenance: Test whether increasing the frequency of expectation breaks causes weaker breaks to be enough to break the illusion;

d) Assess whether the individual's cognitive or emotional charge has any impact on the illusion's resilience: The ease or difficulty of the task at hand (or the subject's level of stress or relaxation, excitement or fear) can affect tolerance to asynchrony.

e) Test whether the stimuli and their expectations breaks are bidirectional: For example, having the virtual stimulus without the presence of the real is different from having real stimuli without the expectation in the virtual. In other words, it is also a valid approach to test whether the illusion is interrupted when the user receives a real touch stimulus without the expectation of this same stimulus in the virtual environment.

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