Astral Body: a virtual reality game for body ownership investigation

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Abstract. As one of the most disruptive human-computer interaction techniques, Virtual Reality (VR) provides a novel way to examine human movements, e.g. when investigating Body Ownership (BO) in the field of cognitive sciences, especially when the visual output diverges from real-world actions. Previous research in BO uses questionnaires and brain imaging, where the former is a highly subjective metric, and the latter is very costly in time, money, and personnel. To answer the question *How can a VR serious game help overcome current challenges of BO assessment?*, we designed *Astral Body*, a VR game that helps cognitive science researchers assess people's level of BO. In the game, players are asked to grab 'flying collectibles' coming from a portal in space. Researchers can inject different types and levels of asynchrony into the arms of the visualized avatar, thus affecting the players' BO experience and perception. Players, in turn, can also report whenever they perceive possible mismatched avatar behavior. In addition, researchers can analyze player data, including looking for unconscious responses, e.g. small adjustments in physical movements to mitigate injected asynchrony. Preliminary results from playtesting and qualitative analysis of *Astral Body*indicate that a VR game can effectively help researchers investigate BO phenomena.

Keywords: Virtual reality · Body ownership · Control asynchrony.

1 Introduction

The study of the self has a deep and far-reaching history in philosophy from Buddhism and Taoism to Ancient Greece and later philosophers such as David Hume and Descartes. Although it has been a widely discussed topic over millennia, no real consensus has been reached on what the self really means and, from a philosophical standpoint, that might not even be achievable. The scientific field of cognitive sciences, however, has tried to link the domains of psychology, philosophy, and neurology together to investigate the subject and the experiences it produces. Gallagher [7] argues that in terms of the 'minimal self' (an idea of the self unbounded by a temporal dimension) a distinction can be made between *self-agency* (the sense of agency over one's actions) and *self-ownership* of one's actions. The latter is also called *Body Ownership* (BO).

Many BO researchers, such as by Ehrsson et al. [6] and Budai et al. [11], study this phenomenon by both using questionnaires and brain imaging techniques. These questionnaires, although easily deployed, are highly subjective and hard to use in the study of covert cognitive phenomena. Brain imaging techniques are scientifically more objective, but cost a lot of resources in terms of money, time and personnel. Additionally, even when doing research by using equipment such as fMRI, investigating BO dynamically is difficult. EEG can be used in a dynamic setting but there is still no good paradigm to map brain signals related to BO. Real-life BO illusions are also more time-consuming to set up and are hard to perform without the participants having an idea about what is being studied with them.

We pose that by employing an immersive Virtual Reality (VR) serious game, the above limitations can be overcome. Therefore, our main research question is: *How can a serious game overcome the current challenges of BO assessment?* To answer this question we created *Astral Body*, a VR serious game in which players move their hands to grab moving objects from the air. The game allows for the controlled stealthy injection of both spatial and temporal asynchrony between the actual player movements and their visualized counterparts. Many parameters of the game can be configured at will by researchers, so that a variety of experiments can be easily designed, reproduced and/or modified. *Astral Body* collects a variety of player movement data, permitting researchers to measure and analyze the behavior of players, including their reactions attempting to mitigate injected asynchrony. Due to *Astral Body*'s immersive gameplay, experiments are more engaging and have fewer confounding variables, particularly regarding players' awareness of its concrete research purposes.

2 Related work

This section provides an overview of prior research related to BO, using both traditional methods and virtual reality.

2.1 The self and body ownership

Gallagher [7] reviews the concept of the *self* and also differentiates between the sense of self-agency and the sense of self-ownership of one's actions (e.g. the sense of driving or washing) that can also be regarded as BO. If the information received by the body from different sensory modalities such as vision, proprioception, and kinesthetics, all correspond and match with each other, it results in a sense of BO [9]. Previous research proposed various ways to estimate the sense of limb ownership or global body awareness [4], while we are concentrating on the former setting.

BO experiments have been devised in multiple domains, including the study of psychological disorders [17]. The Rubber Hand Illusion (RHI), devised by Botvinick & Cohen [2], is seen as the pioneer and most famous experiment to show the proprioception drift. They describe that mixing experiences from different modalities could be sufficient for a sense of BO in participants, regarding objects that are not physically connected to them. In the platform, one artificial limb would be placed in front of the participants which could be visually observed by the participant, while the real limb was hidden or covered. Then, researchers applied the same stimulus signals on virtual and real limbs. An illusion of BO over the artificial limb would be induced in most cases: participants mislocalized their real limbs to be at the artificial limbs' position.

To further explore the inducements which also lead to BO illusion, various RHI extensions have been conducted. Walsh et al. leveraged a mechanical facility for synchronous finger movement in their platform [18]. As measured by the questionnaires, BO illusions were also reported by a majority of the participants, which demonstrated synchronous body movements as another source for the illusion besides visuotactile stimulus. However, the limited adaptability of the experimental facilities impairs the advancement of experimental methodology within this area of study. Furthermore, the utilization of conventional instruments also leads to issues of inefficiency and reduced data precision.

2.2 Virtual reality and body ownership

Similarly to the RHI, the sense of BO can also be replicated in a VR environment [15,16]. Bourdin et al. investigated the effects of altered visual feedback on unconscious motor and muscular adjustments during limb movement within an immersive virtual reality environment [3]. Participants were instructed to perform a movement of 90 degrees while their virtual arm movement angles were manipulated. The use of sensors to assess BO in their studies, and having users mechanically repeat the arm movement, may not be ergonomically valid and may amplify users' awareness of the purpose of their research.

Yizhar et al. conducted a study on BO using virtual reality [19]. Participants performed the task of lifting and hitting balls while their virtual hands were either incongruent or congruent with their real-world hands. BO was then assessed through surveys filled out by the participants. In their study, a VR scenario was employed; however, some participants reported experiencing ennui. Moreover, their method cannot determine the moment at which participants become aware of incongruities.

Little research has been conducted on the study of BO in the presence of asynchronous elements. The categorization of asynchronous elements can be differentiated into two types: spatial and temporal asynchrony. This distinction is in accordance with the findings of Chancel et al. [5], who showed that the temporal and spatial congruence principles of multi-sensory stimulation are determinants of BO discrimination. In a study [13], participants were instructed to alternately switch between a virtual body closely resembling themselves, in which they described a personal problem, and a virtual character representing Dr. Sigmund Freud, from which they offered themselves counseling. The study found that when the virtual Freud moved synchronously with the participant, a stronger illusion of ownership over the Freud body was experienced, compared to when it moved asynchronously. They primarily examine the impact of temporal asynchrony on BO; however, the effect of spatial asynchrony would also be worth investigating. Andreasen et al. [1] conducted a study on spatial asynchrony, where participants underwent visuo-tactile stimulation on their arms while viewing an object touching a bat wing at three varying spatial displacements between the virtual touchpoint and the actual arm position. The results indicated that a level of BO could be achieved, but the degree of BO declined as the spatial displacement increased. The study only focused on three mappings and further investigation with a continuous and diverse range of scales was not explored.

González-Franco et al. [8] investigated the BO of an avatar viewed in a virtual mirror. This study incorporated elements of both spatial and temporal asynchrony to some extent, under two conditions: a synchronous condition, where the avatar reflected the participant's upper-body movements in real time, and an asynchronous condition, where the avatar displayed pre-recorded actions similar to the participant's movements. Results showed that participants felt a stronger sense of BO in the synchronous condition. However, the approach of pre-recorded actions was limited in revealing detailed information on asynchrony and suffered from a lack of flexibility as different actions may have resulted in varying effects.

Summarizing, current research has identified the following main challenges for BO assessment: limited adaptability of experimental facilities, laborious and costly experiments, and exposed research goals, leading to participation bias [10].

3 Game Design

To address the deficiencies identified above, and capitalize on the immersiveness of virtual reality, we designed and developed *Astral Body*, a serious game that integrates both spatial and temporal asynchrony into its key game mechanics. *Astral Body* has been designed with the purpose of helping cognitive science researchers identify key predictors of BO with a VR avatar. In addition, the game immerses players in a fictive scenario, keeping their focus away from the researchers' intention of evaluating BO. By adopting this decision, bias stemming from research participation could be potentially eliminated, as suggested by McCambridge et al. [12].

3.1 Synopsis

The player, using VR goggles, is placed in a fictive virtual environment, in which they control the visible hands of their avatar. Objects come sequentially floating towards the player, who has to catch and deposit them, one at a time, in a container. The player wears conventional VR hand controllers, in order to track their arm and hand movements. Players are encouraged to reach a proposed threshold score across several levels. In addition, they are invited to press on the controller main button, if on any occasion they perceive something anomalous with the game's responsiveness.

3.2 Main design choices

As a game to be played only once by each player, and for research purposes, it is desirable that the gameplay of *Astral Body* is made accessible to a broad range of participants, without presenting a steep learning curve. We therefore chose for simple mechanics of catching and collecting items, as shown in the main game loop of Figure 1.

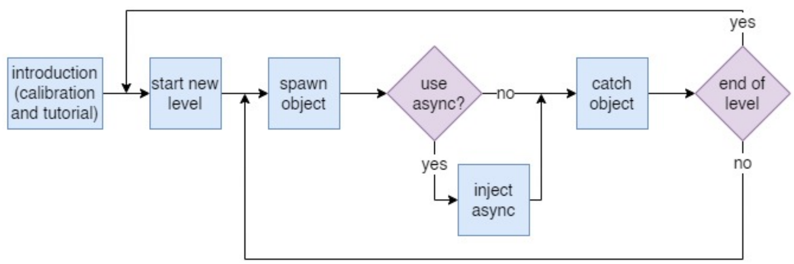


Fig. 1: Main game loop of *Astral Body*, with each level consisting of a series of object catches, possibly affected by asynchrony.

Typically, a game level can take up to 90 seconds to complete as, after all, there is physical movement involved, and one should be given some rest periodically. Initially, game levels operate as normally expected. However, after a while, asynchrony will start being introduced at different levels, according to the settings chosen by the researcher, as discussed in the following subsection.

Players are not informed of the real research goals nor, for that matter, ever hear terms like 'asynchrony' or 'body ownership'. Instead, they are simply instructed to press the 'feedback' controller button might they perceive any game anomalies, as if they were e.g. beta-playtesting the game.

Researchers are offered a large flexibility to configure a variety of input parameters, which help customize in detail the injection of asynchrony (e.g. type, amplitude, frequency, duration, etc.). In addition, logging of the above player data is automatically performed, including asynchrony parameters, possible 'feedback' signaled and its timestamp, so that researchers can then use it for further analysis.

3.3 Asynchrony injection

Our hypothesis is that there will be BO perception as long as the virtual arms closely follow the movements of the physical arms of the player. To assess the extent of this 'closeness', we introduce asynchrony to the movements of the virtual arm. In the context of this game, *asynchrony is defined as a disparity between the movements of the physical arm and of the virtual arm.* This introduction is done incrementally, in a controlled fashion, so that as the asynchrony increases, participants may start experiencing a decline in BO. The expectation is that at some point, the player will feel uncomfortable with the discrepancy between their movements and the respective visualization, and signal the fact pressing the 'feedback' controller button. The game will then record the event, including the timestamp at which the participant reports a loss of control over the virtual body. In this way, we can determine at which point the participants' BO will break due to inconsistency between real arm movements and virtual arm movements.

For the purposes of this research, we consider two types of asynchrony: spatial and temporal. Each type of asynchrony can be configured at each game level, as desired by the researcher. This can possibly include combining the two types in the same game level, whenever desired.

Spatial asynchrony: consists of inserting a deviation between the virtual arm position and that of the real arm. For this, a target displacement vector is computed which is gradually applied to the position of the virtual arm as the actual movement of the arm progresses. Under this scenario, the virtual hand moves together with the player's hand, but ends up at a shifted location, possibly leading to a sensation of movement inaccuracy.

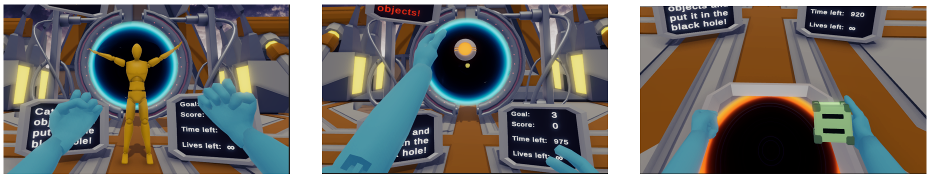
Temporal asynchrony: consists of inserting a target latency in the response of the virtual arm visualized. For this, samples of the actual hand trajectory are recorded in a memory buffer, and are used, after a target delay, to reproduce that same movement on the virtual hand. Under this scenario, the virtual hand accurately ends up at the same location of the player's hand, but with a delay, possibly leading to a sensation of movement latency due to the lagged motion visualization.

3.4 Specific game mechanics

Game level configuration The implementation of multiple levels in the game serves to mitigate the drawbacks of having a player face exactly the same challenges over and over again, which often arises in many experimental trials. Because *Astral Body* aims at helping cognitive science researchers identify key predictors of BO, the game features fully configurable and directly accessible input parameters, including the object spawning rate, the target level scores, etc. as shown in Appendix A.

By offering various levels with differing settings, the game is able to maintain participants challenged and engaged, as well as distract them from the true research objectives. This is instrumental in ensuring the validity and reliability of the data and results obtained.

Introductory level Due to the nature of *Astral Body*, which heavily focuses on arm movements, it is important to avoid disparities associated with the player's diverse height or arm length, to assure that the main player challenge remains the asynchrony mentioned in the previous subsection. Therefore, an introductory level, consisting of calibration and a tutorial, was designed. The *calibration phase* requires players to perform hand-waving actions to record their actual hand positions; see Figure 2a. This information is relevant to help determine the range from which objects will spawn during the game. Subsequently, in the *tutorial phase*, players will play several rounds of the game under guidance, gaining a basic understanding of the game mechanics and learning how to effectively interact with the virtual environment using the controllers. The tutorial phase serves to suppress possible unfamiliarity factors with VR, which might otherwise hinder the players' performance during the experiments and, therefore, negatively impact the accuracy of the collected data.



(a) The player calibrates spawning points by mimicking avatar's motions.

(b) The player reaches out the arms to catch an object.

(c) The player catches an object, drops it in the basket, and scores points.

Fig. 2: In-game footage of game mechanics.

Object catching Following the introductory level, at each game level, the player is tasked with catching objects of specific shapes and colors and dropping them in the basket in front of them to earn points, as depicted in Figures 2b and 2c. The action of catching occurs commonly, is brief in duration and is physically light, allowing for a reasonable amount of data to be easily collected. Additionally, as objects fly towards the player from various starting points, this guarantees a sufficient variety in direction and type of movement, thus reducing boredom. When a player's score reaches the required threshold, they progress to the next level, while a high rate of missed objects results in a failure of the current level. The explicit scoring mechanism helps to ensure that participants are focused on the gameplay rather than on other topics, while also maintaining the enjoyment of the game. As the game progresses to higher levels, it will switch from mostly synchronous to increasingly more asynchronous and challenging. Furthermore, the basket is designed such that participants must deposit the objects in close proximity to its opening. This standardizes the movements performed by all participants, enabling the comparison of movement patterns across individuals, which can potentially be used to correlate with questionnaire data collected by other researchers from this game.

3.5 Data collection

Astral Body logs a variety of data, aimed at providing researchers with insight into the perceptual aspects of BO and the effects of spatial and temporal asynchrony on it. This data includes several key elements, as outlined in Appendix B.

By collecting and analyzing this data in conjunction with research questionnaires, such as the Virtual Embodiment Questionnaire (VEQ) developed by Roth et al. [14], researchers can gain a comprehensive understanding of body ownership at different levels of spatial and temporal asynchrony. Additionally, Confirmatory Factor Analysis (CFA) can be applied to the obtained data to explore the underlying factors and relationships between different aspects of body ownership perception.

3.6 Game style

The art style used in *Astral Body* is inspired in low-poly games, characterized by stylized and simple characters and environments. This was done to avoid heavy rendering demands on low-end hardware, as well as to maintain focus on measuring BO without being overly realistic and risking the 'uncanny valley' problem. *Astral Body* offers a casual and relaxing atmosphere for the participants.

4 Game evaluation

A thorough evaluation of the efficacy of *Astral Body* in assessing the influence of asynchrony in perceived BO levels is currently underway, performed by cognitive science researchers. That is an endeavour that takes many months of careful preparation (including ethical approval), execution and data analysis. In due time, its results will be reported elsewhere.

We did a preliminary study, focusing on how players react to different levels of asynchrony. The evaluation session consisted of playtesting three levels of *Astral Body*, and filling in a survey. All participants played the same levels with the same parameters, to eliminate other interfering factors.

4.1 Experimental Settings

The evaluation session was carried out among college students, and no prior VR gaming experience was required. The participants were simply introduced to the VR hardware and instructed to press the feedback button if they perceived anything unusual during gameplay, without disclosing the game's purpose. They then played three levels, one with no asynchrony, one with spatial asynchrony only, and one with temporal asynchrony only. After completing each level, the participants were asked to fill out a survey immediately. The evaluation session had 6 student participants, aged between 19 and 24.

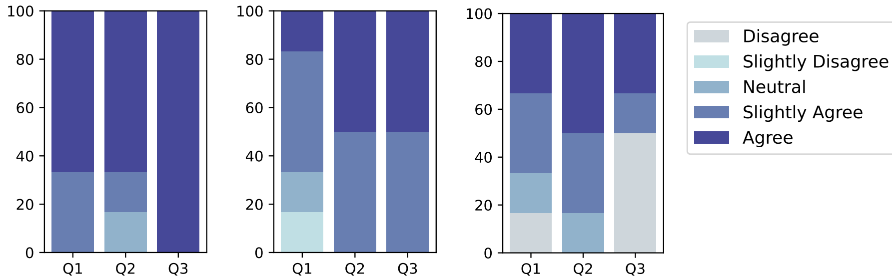
4.2 Results

The results of the survey are summarized in Figure 3. In the level with no asynchrony, 100% of the students felt they were accurately controlling the virtual movements; see Figure 3a. In the level with spatial asynchrony, 16.7% of the participants weakly disagreed that they felt like the virtual body was their own body; see Figure 3b. In the level with temporal asynchrony (Figure 3c), the participants were split: half of them disagreed that the virtual body was matching their own movements. Lastly, most participants agreed that it was enjoyable to control the virtual body.

During the playtest session, we found that around half of the participants totally forgot to press the user feedback button at any point. For those participants who did remember about it, we analyzed their feedback reaction instant, and concluded that it occurred on average, when a temporal asynchrony of 0.2s was injected.

4.3 Discussion

The survey results for the 'no asynchrony' level, see Figure 3a, seem to indicate that all the participants either slightly or completely considered the virtual



(a) No asynchrony (b) Spatial asynchrony (c) Temporal asynchrony

Q1: It felt like the virtual body was my body
Q2: I enjoyed controlling the virtual body
Q3: The movements of the virtual body matched my own movements

Fig. 3: Survey results for 3 different levels.

body was their own body. This is in line with what one could expect for a fully synchronous level, and confirms that in *Astral Body*, BO perception is not affected by factors other than injected asynchrony. The survey also reveals that the majority of the participants enjoyed controlling the virtual body in all levels, including the two levels with asynchrony, indicating that the game is enjoyable to play. Moreover, we confirmed that by increasing temporal asynchrony, players reach a point at which they report feeling uncomfortable with the virtual body response. Although there is a clear need for more experimental data, we can say that *Astral Body* seems to be helpful in assessing the threshold for the acceptable level of asynchrony in BO.

From a comparison of the responses to Q3 between Figure 3a and Figures 3b and 3c, we can clearly conclude that incorporating asynchrony into the game response directly led to a break in BO perception. From a comparison between the responses to Q1 and Q3 for levels with asynchrony, in Figures 3b and 3c, we see there is a larger spreading for the temporal asynchrony level, which was the last level played. This can very well be due to the low n in this evaluation. However, we believe that might also be because after completing the first two levels (no asynchrony and spatial asynchrony), some participants are becoming used to the game and accommodating to its asynchrony.

In short, for this preliminary evaluation, it can be observed that manually injected asynchrony is the sole factor that affects BO perception in the game. This seems to confirm that the *Astral Body* game is a helpful tool for cognitive science researchers to study BO.

5 Conclusions

We presented *Astral Body*, an immersive VR game that helps cognitive science researchers assess the level of body ownership (BO) of its players. To the best of our knowledge, *Astral Body* is the first game combining both spatial and temporal asynchrony, that was developed specifically for such BO research purposes. Another key innovation of this assessment method is that it keeps players focused on the gameplay, rather than exposing them to the actual research goals.

From our preliminary game evaluation, we concluded that the game provides players with an engaging and immersive experience. We also found reasonable evidence that *Astral Body* effectively elicited among its players a sense of BO, which in turn clearly decreased whenever asynchrony elements are introduced in the game mechanics. We can therefore conclude that the *Astral Body* game is a useful tool for researchers to effectively assess BO. Among other reasons for this, the game offers researchers full control over all settings, allowing for a wide range of customization and experimentation, and provides them valuable player data, including asynchrony events and their timestamps.

Despite the game's potential, our evaluation constitutes only a preliminary trial, designed by the developers. Its promising results, therefore, will have to be confirmed by a more comprehensive, rigorous and long evaluation experiment, which is presently underway, lead by cognitive science experts. Its results, involving a much larger and varied sample of participants, should reveal whether the above findings and conclusions can be confirmed and generalized.

In the future, we would like to develop better methods to help effectively explore the collected game data, and possibly expand it with other useful data. A deeper analysis of the in-game statistics, including the identification of new relationships and models, will likely provide a deeper understanding of the factors contributing to the assessment of BO. It might also be interesting to enhance the level of immersion of the game by incorporating haptic feedback to the action of catching objects.

The *Astral Body* game investigates the perception of body ownership with arm movement tasks. We believe that it could serve as a precursor for further research into a variety of disorders, both physiological and psychological. We therefore expect that, in the future, researchers investigate transferring this game concept to other clinical populations, to further understand the causes of their motor impairments.

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Appendices

A. Configuration parameters for research experiments

Input	Usage
General settings	
Player name	Identifier of the participant
Calibration	Toggle whether to enable calibration
Debug	Toggle whether to enable debug window (shows e.g. asynchrony data)
Log frequency	How often the player data is recorded
Task description	The instruction on the game's virtual panel guiding the participants to fulfill the tasks
Object value	The score of an object
Difficulty	
Maximum misses	How many times a participant can miss a catch
Spawn rate	How fast the objects spawn
MaxAmountSpawned	The max number of objects to be spawned at each level
Object speed	How fast the objects fly to the player
Asynchrony	
Async chances	Probability of asynchrony injection
Spatial async offset	offset applied to the virtual arms
Temporal async offset	Temporal offsets
Injection time	Time required for asynchrony to reach the set offset
Async streak max	Maximum number of object spawns before decreasing asynchrony
Async streak min	Minimum number of object spawns before decreasing asynchrony
Game level	
Is target	Whether the spawned object is a target which should be grabbed to gain score
Despawn time	Duration before a spawned object disappears (if it is not grabbed).
Object selection	What objects to spawn
Level name	Identifier of the level
Score goal	Required score to finish the level
Max level duration	How long the participants can spend on one specific level

B. Data logged during research experiments

Data	Usage
Item id	serves as a unique identifier for the target object in the game, allowing researchers to track its behavior and interactions
Item position	provides information about the current position of the target object in the game world, which can be useful for analyzing player interactions and spatial relationships
Left item & Right item	indicate the item IDs held by the player's left and right hands, respectively, if they have already been caught
Player feedback	(left and right) records the timestamp when the participant presses the controller feedback button, which can give measurable insights about perceived asynchrony
Left & right controller position	provide the coordinates of each controller. These coordinates can be used to analyze the player's hand movements during the game, which may contribute to the sense of body ownership
Level duration	indicates the time the participant has spent in the level. This overall duration of the gameplay experience helps researchers understand its potential relation to BO
Spatial asynchrony data	records the spatial offset of the virtual arms in x, y, and z coordinates. This information helps researchers investigate the effects of spatial asynchrony on BO perception, including the player's ability to coordinate their movements with the virtual body
Temporal asynchrony data	indicates the delay introduced into the virtual arms movement. This data helps researchers assess the impact of temporal asynchrony on BO perception and the player's sense of agency