Evaluating visual feedback techniques and Virtual Handheld Object behaviours during collisions

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Interacting with handheld virtual objects in VR opens endless new possible interactions between the user and the virtual world. Although, due to the novelty between the physical and virtual world, discrepancies are sometimes inevitable, and conventional visualisation techniques cause one of these realities to be temporarily broken whilst the discrepancy is resolved. In this study, we propose a new visualisation technique that attempts to maintain both realities simultaneously by having 2 instances of the same object. Through a comparative study conducted with 9 participants, we measured effects on behavioural data and performance along with subjective data on the illusion of presence when experiencing discrepancies with different visualisation techniques. We identified that while the most preferred visualisation techniques are still highly subjective, our proposed technique was far more consistent at communicating the occurrence of the discrepancies, as opposed to conventional methods which were both categorized as glitchy by a number of participants.

1 INTRODUCTION

The picking up of virtual objects is one of the foundational aspects of a VR game or experience. It allows endless new ways to interact with the virtual world, as users become part of Person-Plus-Virtual-Object (PPVO) systems in which the virtual object becomes an extension of their body [3]. The user is then able to use this virtual handheld object to manipulate the virtual world around them, gaining new abilities like cutting though or stabbing other objects. Although, not all objects in the virtual world will react the same way when colliding with a virtual handheld object, and this is even subject to change depending on which object is being held. For example, when holding a virtual tennis racket users can strike a ball and launch it into the distance, but what if the user were to hit a virtual wall with the same racket? Almost all VR experiences will have interactions like this, in which the virtual handheld object collides with an object which should just prevent it from moving, however there is nothing to stop the user from continuing to push the virtual handheld object further in the same direction.

This is fundamentally an issue with the different realities coexisting, and how a PPVO is a combination of objects from both. The user exists entirely within the real world, and their movements are bound by real world physics such as gravity and the normal force of objects. The users actions in the real world are translated into the virtual world, allowing them to pick up objects which exist exclusively in the virtual world. When this happens, the movement of the object is bound by the real world physics acting on the users movements, as well as the virtual world physics being applied to the object, which is what allows virtual object to push and interact with the virtual world. When the user then moves in the real world which causes the virtual handheld object to move into the same space as another immovable virtual world object, the behaviour of the virtual handheld object is undefined. Since this is a physical impossibility in the real world, developers tend to use 2 different techniques to overcome this issue, as without technologies such as substitutional reality or active haptics [23] [17], such events are impossible to prevent.

The techniques for object behaviour during a collision can be categorised based on which reality they conform with. When handheld virtual objects conform with the virtual world physics, they move with the user until a collision occurs. If the user then continues the movement, and the handheld object is unable to pass through the other object, it will remain at the point of collision and maintain its own internal physics; hereafter referred to as "object position maintained" and found in section 1 of Figure 1. Alternatively, if the object conforms with real world physics, the virtual handheld object will continue to move with the users movements, causing it to pass through the other virtual object as if they weren't there at all; hereafter referred to as "PPVO system maintained" and found in section 4 of Figure 1.

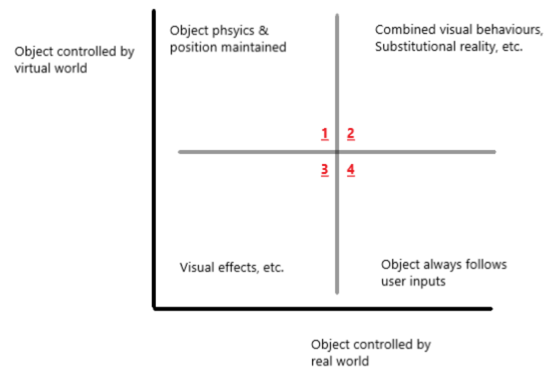

Fig. 1. Exploration of the effects virtual world and real world physics have on virtual handheld objects when they collide with the virtual environment.

Both of these techniques have huge flaws, as they neglect the physics of either the real or virtual reality. Having either of the reality's physics broken gives opportunity for a break in presence (BIP) to occur, which can completely ruin a game or VR experience as users have no sense of being in the virtual reality. In this study, the breaking of one of these physics will be called a discrepancy, and this can either be a discrepancy between the physical world and virtual world when the objects become misaligned (object position maintained), or a discrepancy in the physics, in which the laws of object stiffness and normal forces are broken (PPVO system maintained).

In an attempt to counteract the weaknesses of these common techniques, this study proposes an alternate visualisation technique that shows the virtual world object in 2 positions simultaneous in an attempt to preserve both realities at once. We expect this to help

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user's to resolve the discrepancies themselves in a much quicker time frame, thus avoiding BIPs and retaining the illusion of users being in the virtual world. This is conducted using a systematic approach to compare the visualisation techniques: with questionnaires and interview data used to assess user presences and behavioural data to assess the effects on discrepancy resolution.

2 RELATED WORK

2.1 Interactions

Because interacting with objects in the virtual world is so impactful on user experience, it is no surprise that the majority of research focuses on exploring new ways to do so.

2.1.1 Commercial Devices.

End users typically have access to two primary input devices for their interactions in virtual reality experiences: Hand Tracking and Controllers. While these methods have their advantages and disadvantages, they are both widely considered effective input methods, allowing clear and precise interactions with the virtual world. What makes these input types so successful for a commercial product is that the input makes sense in any context, with users picking up and manipulating virtual objects with their hands using 6 degrees of freedom, just as they would with real objects in the real world. The success goes as far as to giving user's the illusion of being part of a Person-Plus-Virtual-Object [3] system when they are interacting with virtual objects: altering their affordances when they are holding a virtual object. This is almost identical to the effects of the Person-Plus-Object system: a psychological phenomenon in which humans perceive objects being held as an extension of their bodies [24]. The held object can then be used to interact with the world in different ways to those naturally available, such as using a sharp knife to cut other objects or spreading fire with a lit match. Therefore, having the affordances of virtual handheld objects occur in the exact same way as real objects is a main reason hand based input devices are so universally successful as an interaction method.

Despite users being able to successfully manipulate virtual handheld objects with commercial virtual reality devices, underlying issues arise when collisions occur between handheld virtual objects and the rest of the virtual world. Since virtual objects have no presence or baring on the real world, they have no influence over the physical movements that can be made by the user. This means when a virtual handheld object collides with another virtual object, the users movements are physically unaffected by the collision, and only by visualising the collision within the virtual world and using audio feedback can we inform the user of the collision occurring and the outcomes of it. The lack of object stiffness and normal force on colliding objects also means that what would normally be considered physically impossible interactions are unpreventable. Since the user's hand is physically unaffected by the virtual world, when a virtual handheld object collides with a virtual wall, nothing physically prevents the user from pushing the object into the exact same space as the wall, which is the cause of a discrepancy. Instead, developers rely on the use of visual feedback and virtual world mechanics to communicate the discrepancy to the user and guide them to resolve it. Despite this being completely unavoidable, and many potential methods of visually representing the discrepancy being possible, there is no research to determine which, if any, is the most appropriate visualisation technique for communicating discrepancies.

2.1.2 Specialised Systems.

A lot of research has gone into how specialist equipment can be used to provide stiffness and force to virtual objects during collisions to overcome this issue [12] [16]. One prominent technique is through active haptic devices, where physical pressure is exerted on the users body relative to the users movement to give the illusion of stiffness to virtual objects during collisions and interactions [17] [18]. Haptic devices typically come in a few forms: handheld devices [22], wearables such as gloves[1] or large mechanical devices and arms[2]. Different haptic devices each have pros and cons, however given the additional feedback to users which almost identical to the feedback they would expect from a real world object, haptic devices are incredibly successful at making users feel present in the virtual world.

Another technique currently being researched is the use of passive haptics and substitutional reality. This allows users to physically interact with real world objects that are tracked in the VR experience, giving feedback on object weight and stiffness, and then visible impact of the interactions within the virtual world. The scale of proxy objects being researched ranges from the use of a single proxy object that can represent multiple virtual objects [1] to having full scale rooms with each virtual object being mapped to an object in the real world [23]. As with active haptics, almost all research with passive haptics indicates that when the virtual and real world objects are well aligned, users experience a much higher level or presence within the virtual world [8]. And when using a small number of passive haptic objects, this is a very affordable option when compared with active haptic options for providing stiffness to virtual objects.

While the above mentioned haptic systems both massively increase user immersion when interaction with virtual handheld objects, they are both flawed when it comes to being end user products. First off, active haptic devices are incredibly expensive and fragile, making them an off-putting option for commercial products. Additionally, they're designed for specific contexts, such as simulating a stick rotating in your palm [22] or the stiffness of pushing buttons [18]. The contextual limits are another reason that active haptic devices are currently infeasible for commercial VR products, which as previously discussed are designed to be usable for any context or virtual experience. Similarly to active haptics, most passive haptics are also contextually restricted. This makes the majority of them infeasible for commercial products, as you would need an entire dedicated room layout for each experience which is obviously infeasible for end users. Re-configurable passive haptic objects however do seem more appropriate for commercial devices [1], since they can always be contextually relevant. They do however suffer the exact same issues as already available input devices when it comes to virtual object collisions, where objects which only exist in the virtual world

[1]https://www.manus-meta.com/vr-gloves
[2]https://www.haption.com/en/products-en/virtuose-6d-tao-en.html

still provide no physical feedback when the user moves their hand through them, regardless of if they are holding a passive haptic object or not. Such collisions are then at risk of breaking a user's presence in the virtual environment, since the discrepancy between the virtual objects and physical user inputs aren't appropriately conveyed to the user.

2.2 Virtual Hands & Self representations

As the user's inputs are converted into the virtual world using any of these techniques, virtual hands and bodies are shown to visualise the movements and interactions in real time. This presents the user with the illusion of self representation and spatial presence within the virtual world, which studies show to be highly successful [21]. Almost all forms of avatars, from virtual hands to full bodies calculated using inverse kinematics, contribute to creating an immersive experience [15], but they all share a common limitation. If at any point, the users actions in the real world and the virtual representation of them become misaligned or desynchronized, the user's proprioception is broken which can lead to cybersickness and BIPs [4] [23]. This is particularly relevant as we investigate collisions which disconnect virtual objects from virtual hands, especially when we consider that the virtual hands are themselves a form of virtual only object which should be controlled by both the virtual and physical world simultaneously.

2.3 Visualising Handheld Virtual Objects and Collisions

The visualisation of handheld virtual objects during a collision is an issue that was identified very early in the development of interactive VR experiences [12] [16]. The mixture of the realities was even identified as the fundamental issue at this time, but rather than exploring possible ways to enhance the visual feedback to better communicate any discrepancies, research led to augmenting the physical world with haptics, as discussed above. This is a natural progression in the research, as the haptic devices do provide a much more immersive experience, but as a result the advancement of visual feedback techniques has largely been neglected. The techniques proposed as early as 1989 are still in use today, such as Baraff first exploring the concept of simulating non-penetrating rigid bodies [2], which during a VR collision is the maintaining the virtual world physics.

While these techniques do have their advantages and disadvantages at visualising discrepancies that occur between the physical and virtual world, none of them are perfect. In fact, the only method that perfectly prevents discrepancies from occurring are the use of substitutional reality and having every single VR object mapped to a physical object. This, as discussed, is unrealistic for commercial VR experiences and games, so we must appreciate that some interactions will inevitably cause a discrepancy due to the objects not being present in both realities. This is very similar to the issues with locomotion in VR, another research sector focusing on large scale movements. As with interactions, a perfect scenario does exist, with every VR experience having a room the exact same scale that the user can physically move through. This, however, is extremely impractical and unrealistic for commercial VR experiences just as full substitutional reality is for interactions. Instead, many researchers are exploring how unconventional techniques of facilitating locomotion have effects on user presence and performance; many of which are yielding promising results [14] [5]. We therefore propose the exploration of different discrepancy visualisation techniques in the same way, to identify the characteristics and effects on presence for each technique, in an attempt to identify which is most appropriate.

3 VISUAL COLLISION FEEDBACK TECHNIQUES

Some contexts and interactions will have obviously appropriate behaviours, such as the popular VR game BeatSaber[3] which allows friction-less cutting of any virtual object using swords. Nevertheless, most VR experiences will have unavoidable interactions in which a discrepancy in either the virtual world physics or the misalignment of the user to their handheld object occur. Developers must therefore make clever use of the audio-visual feedback channels they have available (and extremely limited haptics in the form of controller vibrations) to communicate the discrepancies to the user and assist them in resolving it [Fig. 2].

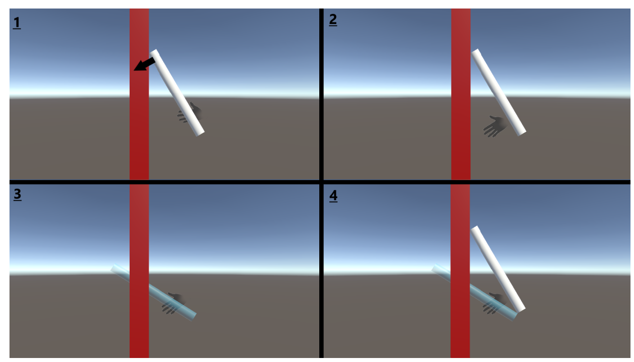

Fig. 2. Examples of Visual Collision Feedback Techniques. (1) The direction of movement of the virtual handheld object when a collision occurs. (2) The misalignment between the user hand and virtual object when the objects position is maintained. (3) The PPVO system being maintained as the object clips through the other virtual objects. (4) Our proposed combination of techniques 2 & 3

3.1 Maintain the object position

The first behaviour for visualising collisions is to maintain the object position and physics when a virtual object collision occurs [Fig. 2 - 2]. When the user moves the handheld virtual object and a collision occurs, the users hand will continue to move, unaffected by the event, whereas the virtual object will remain at the point of collision as to not break the virtual world physics. This is one of the default behaviours for virtual reality games and experiences, as it's enforced by the game engine physics used for development. In terms of virtual reality, the affordances are maintained as objects have the illusion of stiffness and interact with one another in the expected way (the wall stops the object movement). This, however, causes the user's hand to become misaligned with the object they are holding, which has

[3]https://beatsaber.com/

the potential to cause a break in presence. In this case the occurrence of a discrepancy is both visualised, as the virtual hand or virtual avatar will be positioned differently to the object, and sensed by the user's proprioception, as the user's body moves separately from the held object.

3.2 Maintain the PPVO system

Another common behaviour for handheld object collisions is to enforce the user's movements onto the object, regardless of any collisions. As seen in [Fig. 2 - 3], as the users had moves and a collision occurs, the handheld object and the users hand continue to move, unaffected by the collision, in an attempt prevent the misalignment of the virtual object from the users position. This clearly focuses on overcoming the presence breaking issues that arise from maintaining the objects position during a collision, giving the user full autonomy over their PPVO system. However, such a behaviour is still not perfect, as the virtual physics are broken when 2 objects occupy the exact same virtual space at the same time. Additionally, the handheld object loses it's ability to interact during a collision to prevent it from interacting with objects on the other side of the wall. Having the virtual world physics be broken during a collision is another an opportunity for a break in the user's presence, since the objects and environment lose their credibility as real object or actually 'being there'. During such an event, the discrepancy is visualised by the objects visibly clipping into one another, as well as the object losing it's expected behaviours to prevent the aforementioned interaction issues. // Depending on the user's perspective, the visualisation of this can be hard to see, making information about the discrepancy less available to the user. To overcome this, some experiences give the handheld object a "ghost" appearance during a collision, intended to highlight the discrepancy as well as reinforcing the idea that the object has no physical properties, and thus can't collide with other objects. The example in [Fig. 2 - 3] is an example of providing this ghost appearance during the collision.

3.3 Simultaneous behaviours

Since both the common behaviours for handheld object collisions each give opportunity for breaks in presence, we are proposing an alternative technique that combines the current efforts in an attempt to combine their strengths [Fig. 2 - 4]. For this technique, as the user moves their hand and a collision occurs, an instance of the virtual handheld object will remain at the point of collision, while a second ghostly instance will continue to move with the users hand, unaffected by the collision. Theoretically, the discrepancies produced by the two objects are opposites, and if virtual reality experiences where to provide both types of visual feedback simultaneously, participants would see the virtual object conforming to the virtual physics, in addition to seeing ghostly version still moving with their inputs. Referring back to Figure 1, this technique maintains both the realities, placing it within the top right quadrant along with substitutional reality and active haptics.

Having 2 directly comparable visualisations of the object clearly highlights the event of a discrepancy, which will assist users in resolving it. The obvious issue for combined behaviours is that there exist 2 instances of the exact same object in the virtual world at the same time, which could provide an opportunity for a break in presence. Although, we hypothesise that given participants will have a much clearer visual representation of the discrepancy, they will be able to resolve it faster; returning them to a fully consistent virtual world where they are much more likely to feel present.

3.4 Determining the end of a discrepancy

The final factor effecting object behaviour is to determine when a discrepancy has been resolved. This sounds simple on the surface, as you can easily check if 2 objects are overlapping using a game engine, although with virtual handheld objects there is potential for presence breaking events. As seen in [Fig. 3], it's possible that a user would pass the handheld object entirely through another object, resulting in the objects no longer overlapping. By definition, the handheld object and the wall are no longer colliding, but this goes against all real world logic as it completely breaks the laws on physics [Fig. 3 - 2]. The alternative would be to use one of the discrepancy visualisation techniques described above and guide the user to return the handheld virtual object to the point of collision before giving them full control over the virtual object again [Fig. 3 - 1].

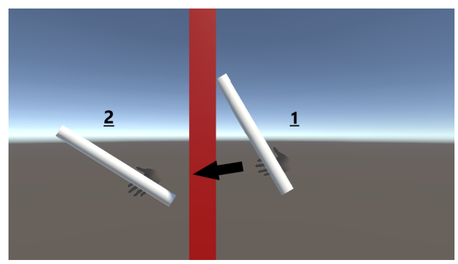

Fig. 3. Visualisation of possible discrepancy endings. (1) The discrepancy ends when the virtual object is returned to the location where the discrepancy began. (2) The discrepancy ends when the users hand is in a location where no collisions occur.

The most appropriate of these methods is, again, a point of contention among the VR community, although certain pairings of discrepancy ending behaviours and visualisation techniques do seem to occur more frequently in games. Typically, they are chosen to compliment each other: so a game which maintains the PPVO system wouldn't require the user to return to the point of a collision, allowing them to resolve the collision in any direction. On the other hand, experiences which maintain the object position during a collision tend to require the user to return to the object to regain control. These pairings make logic sense from an outsider perspective, but through a thorough evaluation of the possible behaviours and feedback techniques we hope to determine if there exists a most appropriate combination to maintain user presence for experiences without a specific contextual reason to deviate. We will also explore how the different combinations of visualisation techniques effects user presence for both discrepancy ending behaviours.

4 STUDY

To explore the different characteristics of the current visualisation techniques, and compare our proposed new technique, we have designed a systematic study to explore the varying visualisation and behavioural configurations.

4.1 Virtual Environment & Context

In order for the experiment to focus entirely on the impact of the handheld object behaviours, we need to design a virtual environment which minimises the possibility of other features causing a break in presence. Therefore, we have defined a number of characteristics within the virtual environment that will serve as control factors on the user's presence.

4.1.1 Hardware.

First of all, the VR device being used should remain constant. This is to ensure factors such as image quality, frame rate or FoV are the same across all participants, and therefore cause no deviation on task performance or baseline presence [25] [6]. For every experiment, we are using the Meta Quest 2[4], which comes with controller and hand tracking support, 1832 x 1920 resolution per eye and 6 degrees of freedom without the need of external sensors.

4.1.2 Avatars.

Second, as we want participants to feel present within the virtual world before the collision discrepancies occur, virtual avatars will be used. More specifically, we will be making use of the Metaverse Avatars[5], since they are easily integrated into the VR experience and make use of highly accurate body tracking. Unfortunately, since participants creating their own personalised avatars would increase the duration of experiments, we have opted to use the default Meta Avatar for this experiment. Notably, these avatars are not high fidelity and are only partial representations (only upper body). While there is still some academic debate on the extent at which the fidelity of avatars can effect users perception of objects, the illusion of ownership and ability to identify interactions correctly is shown to be equal among different avatar fidelity's [15]. Due to this, the use of low fidelity avatars will not only save on computing resources, but still provides all the benefits we need to ensure the participants can feel present within the virtual world.

4.1.3 Context.

For the environment, it's also important that all participants have the same affordances for the objects within. That is, when a participant is using virtual handheld objects to interact with their surroundings, they expect the same (or at least very similar) behaviours. Given we also want to facilitate frequent collisions between the virtual handheld objects and the environment, we decided the most appropriate context for the study would be a kitchen environment. Participants will then perform a number of cutting tasks using a virtual knife object. The affordances for cutting with a knife is a behaviour which all participants will understand. This will then provide a baseline interaction to get participants familiar with the feeling of moving and performing actions within the virtual environment before we introduce interactions that cause a discrepancy.

[4]https://www.meta.com/gb/quest/products/quest-2/#overview
[5]https://www.meta.com/gb/avatars/

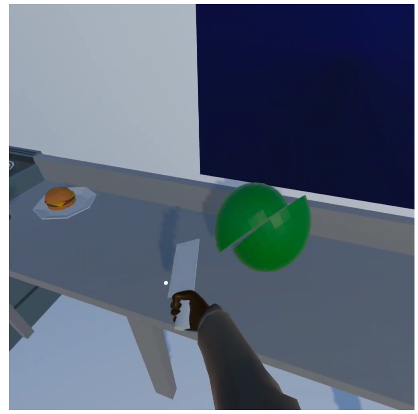

Fig. 4. Participant cutting a virtual object using a virtual handheld knife object as part of our study.

4.2 Methods

When it comes to observing and understanding participant behaviour within a virtual reality environment, the academic community is, again, divided over the most appropriate method. For usability and immersion research for non-VR experiences, subjective data is often gathered using questionnaires comprised of Likert Scales or n-alternate choice methods as well as by conducting interviews [13] [10]. These provide quantitative and qualitative data for the opinions of the participants and are widely considered successful and representative methods of doing so.

Conversely, in virtual reality research suggests that questionnaires are an inaccurate method of collecting data on user immersion, since the difference between focusing on the experience and answering questions can cause a break in presence. Methods to try and minimise this break in presence in an attempt to gather more reliable self-reported data explore concepts such as embedding the questionnaires into the VR experience, sometimes even as a game element [19] [20]. And while the research suggests that in VR questionnaires are less invasive in terms of disrupting flow of tasks, it is clear that breaks in presence still occur between actually completing tasks and completing the questionnaires, even when their embedded into the VR experience. Despite the slight correlations, the lack of conclusive or statistically significant findings to determine at which point a BIP is most likely, or even quantifying how likely they are, we will be asking participants to complete them outside of VR, so that we can follow up on their choices and opinions in an interview immediately after. As for the questionnaire itself, Schwind identified that the igroup presence questionnaire (IPQ)[6] is most appropriate, as it offers an excellent balance between reliability and reasonable completion time [20]. Developed by Schubert et al, the IPQ is the culmination of countless research papers into 14 Likert Scales focusing concisely on the illusion of presence within a virtual space. Since presence is exactly what we are observing through variable collision techniques, the IPQ is a perfect fit for our study, and participants will

[6]https://www.igroup.org/pq/ipq/download.php

complete this form twice, once after each of the discrepancy ending techniques.

As an alternative to questionnaires, some researchers are instead investigating the use behavioural data gathered by the device during a user's VR experience to try and identify trends in presence and immersion. For example, Kamińska performed a pilot study on using objective data such as hand tracking and EEG sensors to attempt automating usability testing in a VR setting [11]. The use of objective data, such as number of collisions, error rates, or task completion times, are very useful indicators for usability and learning rates, both of which are factors we know are linked to the users immersion and presence [7]. Despite the study not giving conclusive evidence on the automation of the user experience testing, it clearly shows that the objective data gathered can supplement subjective findings from questionnaires. Additionally, the behavioural data is gathered in real time while the user is full present in the virtual environment, making it robust to any of the previously discussed issues with BIPs or self reported data. We will therefore be gathering behavioural data about any discrepancies in real time, such as duration, magnitude and overall number of occurrences. We will then be able to directly compare the effects of different behaviours and visualisation techniques on the users ability to resolve discrepancies, providing insight into the underlying reasons for user opinions using objective data.

4.3 Experiment Procedure

Since there are 3 different visualisation techniques we want to study, as well as 2 methods of ending a discrepancy and 2 input systems available on commercial devices, our experiment has to account for 12 potential configurations. Given this large quantity of configurations, we split the experiment into 4 district sections. This provided opportunity for participants to leave VR to complete questionnaires and interviews. The changing between certain configurations also supports pauses in the experiment flow, since BIP are almost guaranteed when participants change input devices. Pauses also help break up the repetitive nature of the study. Given the context and tasks completed by the participant must remain as similar as possible, by the time user's have cut through 50+ pieces of food, their motivation and engagement is likely to have declined. Having participants experience the experiment over numerous VR sessions helps maintain such motivation and spatial reasoning [9].

The experiments begin with participants being placed into the virtual kitchen environment and picking up a virtual knife. Once this is done, the participants are instructed to cut the large green fruits in front of them, using a faint seem to guide their movements. Once a fruit is cut, it falls in half and a new one is placed in from of participants on the counter. After continuing to cut a few fruits, the knife will become blunt, preventing it from cutting the next fruit it collides with. Users then attempt to cut as before but instead the virtual handheld knife can't cut the object and the users hand continues to move through the object; resulting in a collision discrepancy. One of the randomly selected visualisation and discrepancy ending behaviours is shown to the user, and they must resolve the discrepancy to continue. When resolved, they can continue to cut fruits as before and the next visualisation technique is silents applied to the knife for when the next discrepancy occurs. Participants repeat this until all configurations in that category are complete, and they are removed from the VR experience to complete the IPQ and a short interview. They then re-enter the experience and complete the remaining configurations.

5 RESULTS

5.1 Interviews

From the interviews conducted during the breaks, there were 2 main themes that arose from the participants comments.

Visualisation Preferences

Multiple participants stated their preference for the combined visualisation technique.

P2: *"I preferred when I could see both (combined visuals), because I could see where I was supposed to go back to."*

P3: *"Seeing the 2 objects (combined visuals) made it clear that it didn't work but the others just felt glitchy."*

P7: *"I liked seeing both (combined visuals) because I could see the difference"*

Although, a few participants didn't even comment on the ghost aspect of this technique, saying it was just the object position being maintained that informed them on the discrepancy.

P1: *"It was clear when the knife stopped (object position maintained) that it didn't cut right."*

And a few participants even expressed their preference for the PPVO system being maintained.

P4: *"I liked when the knife moved with me because the others felt like they limited my movements."*

"Glitchy" Behaviour

A number of participants did comment on some of the visualisations and behaviours appearing "glitchy" whilst they were completing the tasks, and upon reflection.

P1: *"I didn't know if it was supposed to be acting that way (maintained PPVO visual), like I couldn't tell if it was cutting or not."*

P3: *(whilst interacting with the maintain PPVO visual) "Is it always this glitchy?"*

P5: *(whilst interacting with the object position maintained visual) "Is it (the virtual knife) supposed to get stuck?"*

Ditching a collision

In addition to the interviews, we also observed participants during their attempts to resolve discrepancies. A very common occurrence across almost all participants was the ditching of a discrepancy when they were unsure on how to resolve it. This involved the user dropping the virtual knife object when their hand became greatly misaligned from it or when the knife clips into the food they tried to cut without having an effect. What's particularly interesting about this observation is that not all participants ditched discrepancies on the same visualisation or discrepancy ending techniques, but instead it was highly subjective.

5.2 Discrepancy Resolution Performance

In this study, the discrepancy refers to the time which the participants hand is misaligned from the virtual handheld object whilst it's

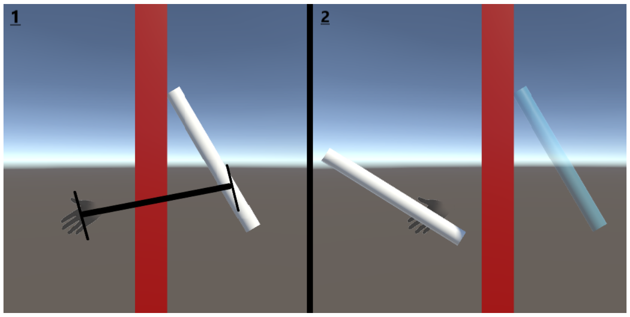

Fig. 5. Visualisation of the magnitude of a discrepancy between handheld object and hand placement (1) and a physics breaking discrepancy (2)

colliding with other virtual objects. It's critical to note that when the virtual object behaviour is to maintain the PPVO system, there is no discrepancy in the conventional sense. Instead, the discrepancy is the disbelief that the virtual object does not behave as a real object would, an effect that technically has no discrepancy in terms of misalignment or changes in object movement, but instead on illusion and therefore potentially causing breaks in presence. Therefore, most of the behavioural data on the discrepancies is only applicable to the maintain object position and combined behaviours. Instead we must rely on subjective data from the IPQ and interviews to understand the effects of the maintained PPVO system in contrast to our proposed combined method.

5.2.1 *Number of Discrepancies.*

The number of discrepancies that occur during each task gives an insight into how frequently participants terminate a collision before they are able to resolve the discrepancy. This is typically the case when participants are confused about the interaction or are unable to instantly resolve the collision discrepancy themselves in the same technique as the previous task. 4 discrepancies must be resolved successfully in order for the given task configuration to be complete, so any deviation from this is the participant dropping the handheld virtual object prematurely.

The configuration that caused the least amount of additional discrepancies was the virtual object position maintenance with the discrepancy ending whenever the user is in a valid position, having a mean of 4.2 ± 0.7 encounters. This is followed closely by the combined visuals and the same discrepancy ending rule at 4.4 ± 0.7 encounters. The discrepancy ending technique that requires the user to return their hand to the point of collision encountered far more discrepancies on average, with the combined visual having a mean of 5.8 ± 2.3 encounters and the object position maintained visual with 6.2 ± 2.0.

5.2.2 *Average Discrepancy Magnitude.*

The configuration with the smallest mean for discrepancy magnitude was the object position maintained visual combined with the discrepancy ending when the user returned to the point of collision, having mean on 0.147m ± 0.051m. The combined visual with the same discrepancy end was the next shortest on average duration

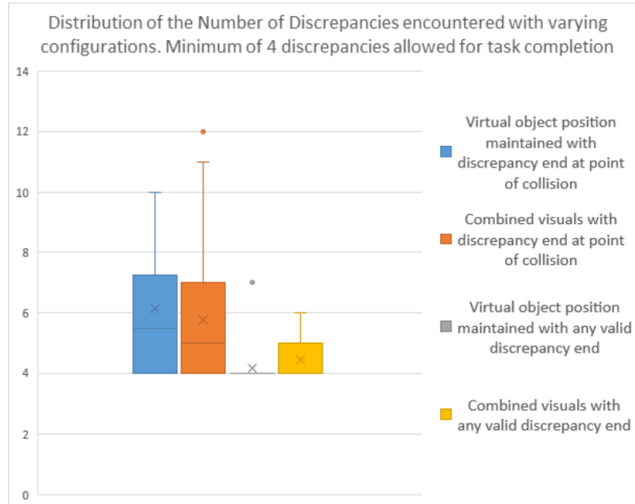

Fig. 6. The number of collisions between the food and the virtual handheld object that cause a discrepancy.

at 0.150m ± 0.048m. This is closed followed by the combined visuals with any valid discrepancy end configuration, with 0.152m ± 0.060m, and finally the object position maintained visual with any valid discrepancy end at 0.190m ± 0.100m.

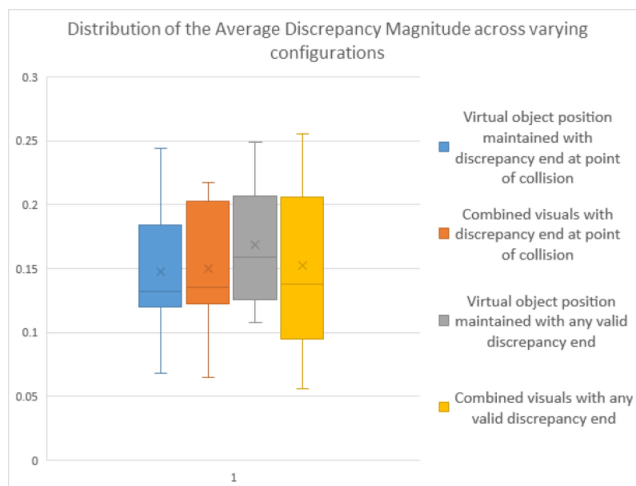

Fig. 7. The magnitude of the discrepancy, as measured from the point at the start of the discrepancy.

5.2.3 *Average Discrepancy Duration.*

The average duration for a discrepancy is shortest when the visual technique is to maintain the virtual object position and the discrepancy ends whenever in a valid position. This has an average duration of 0.3857s ± 0.1248s, which is almost identical to the combined visual under the same discrepancy behaviour; 0.3863s ± 0.1515s. The object position maintained visual behaviour that requires the participant to return to the point of collision to resolve the discrepancy is the next shortest, at 0.4844s ± 0.1513s, with combined visuals and discrepancy end at point of collision closely behind at 0.5041s ± 0.1571s.

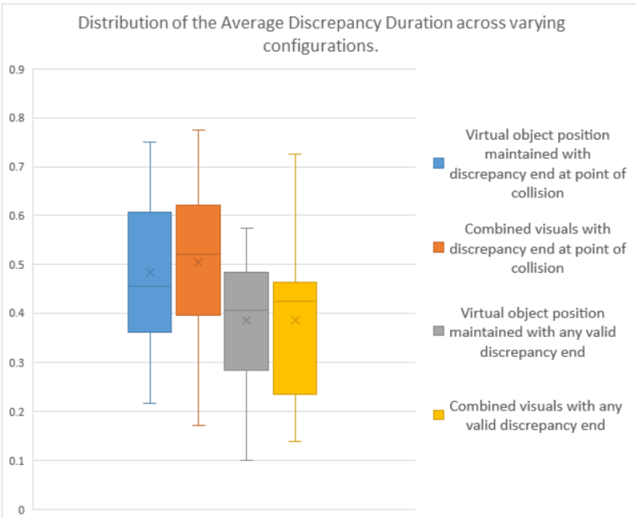

Fig. 8. Average discrepancy duration, individually measured to the closest 0.05s.

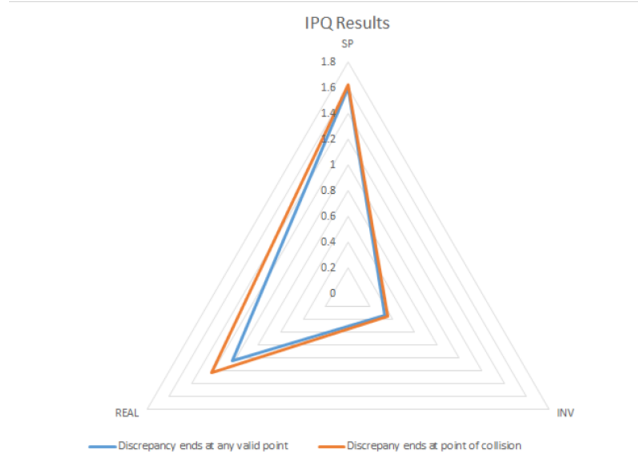

Fig. 9. IPQ Results. (SP) Spatial Presence - the sense of being physically present in the Virtual Environment. (INV) Involvement - measuring the attention devoted to the Virtual Environment and the involvement experienced. (REAL) Experienced Realism - measuring the subjective experience of realism in the Virtual Environment

5.3 IPQ results

Conducted on both occasions the participants leave the VR experience, the IPQ gives quantitative data that we can use to compare preferences between the 2 discrepancy ending techniques. For this study, we translated the result scale from 0 to 6 to -3 to 3, as this better represents the positive or negative connotations of the findings. It's clear that when the discrepancy ends at any point, and when it ends at the point of collision, the perceived spatial presence (SP) for participants is almost identical, having values of 1.62 and 1.60 respectively. The same can be said for the participant involvement, with values 0.33 and 0.36. The only substantial difference can be seen in the illusion of experienced realism, where the discrepancy ending at the point of the collision is seen as more realistic than allowing any end point, offering a mean score of 1.22 as opposed to 1.04.

6 DISCUSSION

6.1 Visualisation Techniques

The overall behavioural data on the discrepancy resolutions under different visualisation techniques show little deviation, with the object maintained and combined visuals both performing very consistently across the different metrics. This would support the idea that the choice between the visualisation technique is redundant, but this is very misleading. The observations and interviews clearly identified that the preferences and capabilities between individual participants varied massively, with each technique being someones favourite. Given that the spread in preference is relatively even, it's unsurprising that the average discrepancy resolution data seems to represent the different techniques as almost equal, since they both contain a proportion of participants who disliked the technique or felt disconnected from the virtual world.

If we instead look at individual cases for the discrepancy data, these are much more similar to the findings from our interviews. Figure 10 shows the distance of the participants hand from the point of collision as they resolve several discrepancies. The top 2 graphs show participant 6, who clearly had much greater success at resolving the discrepancies with the object position maintained visualisation. Comparatively, participant 8 (bottom 2 graphs) had the opposite response, encountering far fewer discrepancies and of smaller magnitude when using the combined visualisation technique. In a vacuum, each participant showed contrasting behavioural data towards specific configurations, just as they expressed during the interviews. The difference between this and the overall data shows the clear misrepresentation of the average discrepancy resolution performance. Instead, the presence and performance is highly dependant on the individual, rather than there being a single technique that is appropriate for all cases.

While there is no perfect visualisation technique that works for all participants, our proposed combined effort did show some interesting results. The discrepancy resolution data is widely the same as with the object position maintained technique, meaning that participants were no quicker at resolving the discrepancies as we had hoped when proposing the combined technique. However, during the interviews, the combined visualisation technique was the only technique that was not once categorized as glitchy, and all participants were observed to resolve all discrepancies without the need

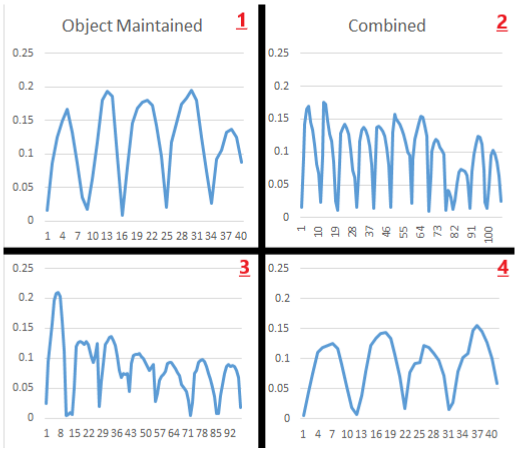

Fig. 10. A comparison between discrepancies encountered by Participant 6 (TOP) and Participant 8 (BOTTOM) between Object maintained visuals (LEFT) and combined visuals (RIGHT). This configuration uses Hand Tracking and the discrepancy ends when returned to the point of collision.

for assistance when using this visualisation technique. The combination of the real world movements being represented along with the virtual world physics being maintained presented the discrepancy as an inevitable and recognized occurrence, instead guiding users to fix the 2 misaligned realities rather than abandoning one to maintain the other. Referring back to the graph on object physics [Fig. 11], we can see that this is achieved by maintaining both the virtual world and real world physics simultaneously, in the same way as substitutional reality or active haptics, but without the need for additional hardware.

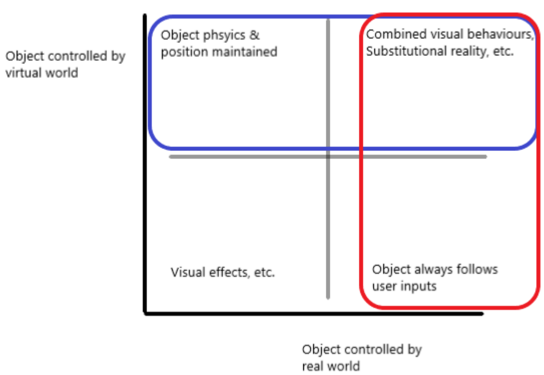

Fig. 11. Graph representing how the real and virtual world physics affect a handheld virtual object, with the effects of the combined visualisation technique highlighted.

Despite the proposed combined visualisation behaviour combining the positives of both other explored techniques, it's still not a perfect solution and would not be suitable for every context or experience. The combined behaviour was not even the top preference for all participants in this study, despite it being far more consistent and understood as expressing a discrepancy. Therefore, we propose that the combined visuals technique is a strong default for VR experiences and games that don't have a specific reason to choose an alternate technique. That's not to say that the other techniques are completely redundant and shouldn't be an option. Similarly to how in many VR games users are given the option to change the locomotion method, the option should be available for users to pick one of these other techniques should they have a different preference. These 3 choices are also not exhaustive of the possible visualisation techniques, and more design and study should be conducted to explore different techniques to explore how contexts, use cases and other parameters effect their performance. Ultimately, this study hopes to open up the discussion of different discrepancy resolution techniques within the academic community, and contribute to the creation of a resource similar to the Locomotion Vault[7] for different discrepancy feedback techniques and their characteristics.

6.2 Discrepancy Resolution

The discrepancy resolution behaviour had 2 distinctly different effects on participants during this study. When the discrepancy was allowed to end at any valid position, the discrepancy measurements clearly show a significant decrease to occurrences, magnitude and duration across both measured visualisation techniques. However, this is juxtaposed by the results of the IPQ, which clearly indicate the virtual reality experience was less realistic to participants of the study with this behaviour. The alternative method explored in this study was to define the end of a discrepancy once the user had returned their hand to within 0.04m from the point of collision. This shows that the speed in which a participant was able to resolve a discrepancy has no correlation to the effects of perceived realism, instead it's the physics and behaviours of the objects which create the illusion of realism for the virtual reality experience. This study identifies that, out of these 2 behaviours, the discrepancy ending at the point of collision is better for maintaining a realistic virtual environment by aligning the virtual world physics more closely with real world physics, although there is still a great deal of study that needs to be conducted to explore alternative methods of ending a discrepancy and determining the most appropriate parameters for these.

6.3 Relationship with avatars

The final thing worth discussing is the application of these findings to virtual avatars and hands. In this study, we have explored how participants interact with handheld virtual objects during collisions, where the object only exists within the virtual world and is being actively controlled by the participant movements. Using this same definition, the virtual hands or avatar that is being constantly mapped to the users movements could also be considered a virtual object, or at least a proxy object since it's the mapping of the movements and gestures of a real life hand. Interestingly, the movements of virtual hands is exclusively mapped to the user movements, which in some way could be defined as maintaining the PPVO system. It also allows all the same behaviours as maintaining

[7] https://locomotionvault.github.io/

the PPVO system, such as reaching through virtual walls and interacting with objects on the other side. The HMD is also interestingly a similar issue, with many games and experiences allowing the user to push their head through a virtual object and view the other side. Obviously, the user's head has all sorts of nuances when it comes to allowing or preventing movements, and the techniques discussed here are not applicable to the HMD in the same way they are with tracked hands. This is however a very interesting evolution of this study, since discrepancies are also unavoidable between the user's movements and virtual objects and a systematic study evaluating the different techniques for resolving them could have countless applications.

6.4 Shortcomings & Limitations

While this study does present some interesting observations about the performance and characteristics of different visualisation and discrepancy ending behaviours, its worth noting that due to the nature of the findings and the number of participants, most of these results are not statistically significant. Additionally, the study covers a very specific context, and whilst we did our best to choose an appropriate virtual environment and versatile task; different contexts, tasks or even hardware have the potential to yield different results.

7 CONCLUSION

Through a comparative study of different collision discrepancy visualisation techniques and discrepancy ending behaviours, we have identified a new visualisation technique that shows some promising initial findings at maintaining users presence during a collision discrepancy. Our study compared behavioural data of occurring discrepancies alongside subjective data on presence and preference using IPQs and interviews. These identified that the visualisation technique preferred by users is extremely subjective, and there is still no one perfect solution. Despite this, our proposed technique was highlighted as the most clear across all users, expertly showing the virtual reality can comprehend the discrepancy and guide users to resolve it; as opposed to the traditional techniques which were both categorised as being glitchy. We also identified trends between how a discrepancy should be allowed to end, concluding that a discrepancy should be resolved by the user returning to the point of collision as opposed to allowing the user to pass completely through objects, as this provided higher levels of experienced realism as identified by the IPQ data. We do however suggest that further research should be conducted to yield statistically significant results, as well as explore other possible techniques that could maintain the physical and virtual world physics simultaneously during a discrepancy [Fig. 11].

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