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Adaptation of interaction mechanisms in Virtual Reality shopping environments for people with upper limb motor difficulties

Rubén Grande,[†1], Vanesa Herrera, [1], Carlos Glez-Morcillo[1], Ana de los Reyes[‡2], José J. Castro-Schez[1] and Javier Albusac[1]

Abstract

In recent years, there has been research and exploration into the development of new shopping experiences within the field of electronic commerce (e-commerce). One of the technologies that can offer a more immersive shopping experience is Virtual Reality (VR). Retail giants such as Amazon and Alibaba Group have begun to use it. The technological advancement of VR, motivated by its use in various domains like e-commerce, has driven the development of software tools like APIs which allow developers to easily develop applications for these devices. One of the latest technologies included in recent VR headsets is hand tracking, which allows users to use their own hands as an input method to interact with the virtual environment. However, software tools for the development of VR applications are not fully adapted to include accessibility options for people with motor difficulties in their bodies, making it very difficult for these people to use this technology with both controllers and hand tracking. To promote accessibility options in the use of VR shopping environments, this study will present the adaptation of a set of interaction mechanisms, among which we highlight: automatic object grabbing, release of grabbed objects, navigation through the environment, attraction of distant objects, and interaction with the shopping cart. These adaptations will be made using Meta's API for Meta Quest devices as a base. The adapted environment has been tested by healthy students from the faculty and one of them with reduced mobility in the left half of his body after suffering a stroke. In this paper, we present the feedback provided by the volunteers, as well as the verification that these interaction mechanisms meet our expectations. This is an essential previous step to carry out a planned experimental session with patients with spinal cord injuries and therapist at the National Hospital for Paraplegics in Toledo (HNPT).

CCS Concepts

• ***Human-centered computing*** → ***Virtual reality; Accessibility systems and tools;*** • ***Social and professional topics*** → *People with disabilities;* • ***Applied computing*** → *Electronic commerce;*

1. Introduction

The field of e-commerce has grown and evolved at a significant pace over the last decade, driven by an increasingly digitalized society. COVID-19 provided a substantial boost to the widespread use of e-commerce services due to pandemic-related restrictions, which motivated companies to incorporate these services [HWN*22, DHKM21].

Another field that has experienced considerable growth Virtual Reality (VR), where tech giants such as Meta or Apple have invested significant resources in both the development of VR devices and Software Development Kits (SDKs) for these devices. Due to the growth of this technology, research and integration into e-commerce platforms are beginning to provide new shopping experiences [CRS23]. The use of these technologies offers an immersive shopping experience closer to traditional shopping than e-commerce platforms, while still offering the possibility to shop from anywhere [PSPV19, KSP20]. Some studies have shown that the shopping experience with VR is very similar or superior in hedonic aspects to traditional shopping, as well as being more enjoyable [XCG*24]. Furthermore, the use of Artificial Intelligence (AI) techniques can significantly improve these immersive experiences, offering recommendations based on user preferences and profiles or integrating agents to assist in shopping [CRS23].

In a future where VR is expected to be one of the dominant technologies in the field of e-commerce, interaction mechanisms must be adapted for people with various difficulties so that they too can comfortably use these VR applications. However, prototypes proposed in the literature on VR Shopping environments and VR applications are completely or partially lacking in accessibility options, leading to inequality for these individuals, which has to be avoided [Fra17]. VR has been used in applications to aid in treating diverse disabilities, such as autism in adolescents [MYS21] or schizophrenia [PHF21], in which tasks like making purchases in virtual environments that simulate supermarkets were significant.

[†] Department of Information Technologies and Systems, University of Castilla-La Mancha, Paseo de la Universidad 4, 13071 Ciudad Real, Spain
[‡] Biomechanics and Technical Aids Unit, National Hospital Nacional de Parapléjicos, Carretera de la Peraleda s/n, 45004 Toledo, Spain

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However, to the best of our knowledge, there are no works or applications that address the adaptation of interaction mechanisms in VR shopping environments for individuals with upper limb motor difficulties. People who have suffered cerebral strokes or spinal cord injuries often experience significantly reduced mobility in these limbs, especially in the hands. This makes the use of *controllers/joysticks* of VR devices more difficult for them [HMA*]. Studies have shown a preference among most patients with upper limb motor issues for interacting with their hands rather than controllers [JED*22]. Moreover, the use of hand tracking technology, integrated in recent years into VR headsets, provides a more natural and traditional shopping experience.

However, the difficulty in articulating certain gestures or reduced wrist and finger mobility can seriously hinder certain individuals' interaction in virtual shopping environments. This is because the APIs provided for the development of VR applications rely on gesture detection for, for example, grabbing an object, at certain thresholds that must be surpassed, or gestures that require specific finger and wrist positions and orientations. Given these difficulties, we see the need to adapt various interaction mechanisms provided by Meta's API for the development of VR shopping spaces that are accessible. This is an essential first step towards the development and inclusion of accessibility options for individuals with motor difficulties due to spinal or brain damage, allowing them to interact in VR environments, specifically, in virtual shopping environments. Therefore, this work proposes a set of adapted interaction mechanisms whose design allows these individuals to use them in virtual environments.

The rest of the paper is structured as follows. In Section 2, we describe related work on the use of VR in e-commerce and for people with various special needs. In Section 3, we describe the background of this work, including the related project and the target users of the adapted interaction mechanisms. After that, we detail the interaction mechanisms that have been adapted to be accessible for individuals with reduced mobility in the upper limbs in Section 4. In Section 5, we describe the experiment carried out to verify the proper functioning of the adapted interaction mechanisms for their future use as well as the results of this experiment. Finally, in Section 6, we offer the conclusions of this work and the future work that will be carried out.

2. Related work

In this section, we will show existing work in the literature on the application of VR to create virtual shopping environments. Then, we will briefly describe work that has used VR in applications used by people with various disabilities, focusing on those that included shopping tasks in virtual environments.

2.1. VR in virtual shopping spaces

Wu et al. carried out two experimental studies focused on user-generated gestures for interactive use in immersive VR shopping applications [WWQ*19]. As a result, they proposed a more practical methodology for the creation of reliable gestures, diverging from the traditional methods used in gesture elicitation research. One of these experiments was set in a VR shopping environment utilising the HTC Vive headset, involving 32 participants who were tasked with 12 distinct activities, such as object selection, colour alteration, and resizing, among others. However, the specifics of how gesture data was captured and analysed were not elaborated upon by the authors.

Peukert et al. [PPM*19] investigated the impact of immersion in VR shopping environments on the likelihood of users wanting to use the system again in the future. To this end, they set up an experiment with two different scenarios: one offering a high level of immersion using the HTC Vive and another with a lower level of immersion presented on a desktop computer screen. In the more immersive setup, the researchers tracked hand movements and head positions, along with the interaction with products, such as picking up, dropping, or transferring items between hands. They also gathered data on eye movements. The study concluded that the degree of immersion affects the user's decision to revisit the shopping environment, influencing them through both hedonic (pleasure-based) and utilitarian (practical) considerations.

The research presented in [SCK17] described the development and assessment of a VR Online Shopping Environment prototype, concentrating on how user inputs like head movements and speech, as well as outputs through desktop and head-mounted displays (HMD), impact task performance and user preferences and behaviour. The prototype was developed in two versions, using different input devices for the desktop and HMD versions, which altered the way users interacted with it. Following a survey in which participants outlined the pros and cons of online shopping, a prototype was built for both desktop and mobile VR settings, limiting user inputs to voice and head gestures. After a case study analysis, design principles for VR shopping environments were suggested. Later, the same authors created a new VR shopping prototype based on the 'Apartment' metaphor [SHD*18]. This aimed to examine various product selection and handling methods (like grab and beam) and to explore different shopping cart designs: an alike physical basket and sphere located in user's interfaces. This new prototype relied in the HTC Vive headset's controllers for interacting with the virtual environment and the products placed on it. Their study using this new prototype revealed that immersion and user experience were major factors for the participants. They also provided suggestions to mitigate motion sickness and identified which types of products are most suitable for VR stores.

These works present mechanisms for interaction in prototype virtual shopping environments with VR. However, none of them addressed mechanisms for people with upper limb motor difficulties.

2.2. VR for people with special needs

A decade ago, researchers started to study the capabilities of early VR technology for helping in rehabilitation of patients with diverse diseases. Laver et al. [LLR*12] investigated the efficacy of a VR-based simulator for enhancing daily living skills in neurological rehabilitation. Developed collaboratively with occupational therapists and a biomedical engineer, the simulator integrates a realistic virtual environment, a large touch screen, and a specialised shopping cart handle for managing the inputs of the patient. The 15 participants, after an introductory session with the system, were given a timed shopping task to complete. Usability was tested with neurological patients, who generally found the simulator enjoyable and beneficial for rehabilitation, suggesting its potential in improving coordination and cognitive skills. However, feedback indicated a need for improvements in control mechanisms and visual aspects.

More recently, Bedendo et. al [BAD*23] developed a VR system using Unity and Meta Quest 2 headset that allows stroke patients to perform tailored rehabilitation exercises at home, focusing on improving hand function impaired by stroke. This VR system integrates motion tracking devices and VR software to create an immersive, interactive environment for patients. The study involved a multidisciplinary team, including rehabilitation specialists, to ensure the exercises were clinically relevant and beneficial for recovery. The paper reports on the pilot testing of the system with stroke patients, evaluating aspects such as usability, immersion, perceived workload, and simulator sickness. Results demonstrated that the system was well-received by patients, who found the VR exercises engaging and beneficial.

The work discussed in [CNT*22] presented a study on using VR for life skills training in individuals with intellectual disabilities. The study conducted a multicenter randomised controlled trial involving VR-based training, traditional training, and a control group with no training. The participants used the controllers of the HTC Vive Pro headset to perform every task, including grocery shopping. This task was harder in the second training sessions, and required participants to buy more products. Meanwhile, the difficulty was also adjusted by adding background noise or similar items on the shelves. Results indicated significant improvements in task performance and memory span for participants in the VR group compared to traditional and control groups.

Chen et al. [CCY*24] presented a study on the use of a VR-based supermarket for the classification, diagnostics, and assessment of Intellectual Disability (ID). The methodology involved creating a virtual supermarket environment where participants' eye movements, brain waves, and behaviours were recorded and analysed using machine learning techniques to develop an objective evaluation model. Among 22 participants, 14 had a higher degree of ID and 8 had no ID. The devices used were HTC Vive Pro using its controllers along with Looxid Link for measuring brain waves. The objective was to provide a more efficient, effective, and economical assessment method in a safe and reproducible environment, overcoming the limitations of traditional ID assessment methods. Even though the environment was a supermarket, the task flows were not focused on shopping but cleaning and tool selection activities. The results showed significant differences in behavioural data between ID patients and healthy participants, suggesting the feasibility of using neural networks for classification, with an accuracy of 95%.

The study carried out by Adjorlu et al. [AHMS17] to evaluate the effectiveness of VR in training children with Autism Spectrum Disorder (ASD) for daily living skills, specifically shopping. Participants were divided into a treatment group of 4 participants, which underwent VR training, and a control group of 5 participants. The VR system used (HTC Vive with its controllers) recorded data on product interactions, hints requested, and total time spent. The participants were guided through the different shopping tasks, and he could navigate the environment by teleporting due to limited physical space. Results showed improved task completion time for the treatment group in a real supermarket post-VR training. However, the effectiveness score remained constant at 100% for the treatment group and decreased slightly for the control group.

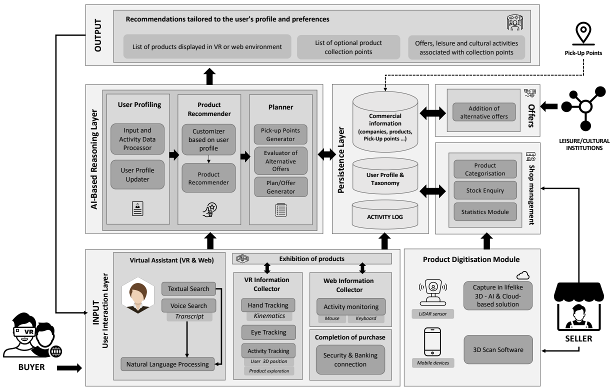

Figure 1: *Architecture of VR-ZOCO.*

The studies presented show how VR environments similar to supermarkets have been used to assist in the rehabilitation, training and assessment of people with various diseases. However, none focuses on adapting interactions for people with upper limb motor difficulties.

3. Background

In this section, we will briefly describe the project within which the current work is situated. The VR-ZOCO project involves the design and development of an e-commerce platform of the same name, based on VR and Artificial Intelligence (AI), aimed at helping small businesses in becoming more competitive in the coming years. Furthermore, we will detail more precisely the conditions of individuals with motor difficulties to better understand the problem we focus on.

3.1. VR-ZOCO Project

Due to the advancements that are happening and will occur in the e-commerce field as discussed in the Section 1, small businesses could find themselves at a competitive disadvantage against large retail companies in the future. The existence of such businesses is vital for society, driving local economies and preserving products with cultural significance to the locality [GGK*23], as well as helping to prevent the depopulation of these areas. Therefore, it is crucial that the gap existing between small businesses and large companies is reduced by enabling the former to also use the new technologies that can transform e-commerce.

Although COVID-19 prompted a change in mindset among small businesses regarding the importance of digitalization, significantly increasing the number of those wanting or starting to digitalize [HWN*22], their financial, human, and technological resources are generally very limited. This is why VR-ZOCO aims to further assist small businesses in their digitalization process, providing a platform they can join to display their products in virtual spaces, helping them overcome a significant barrier of entry in terms of necessary technological knowledge. Additionally, VR-ZOCO is expected to have a positive impact on local economies by suggesting leisure and cultural plans to users based on their preferences, offers, promotions, and the location of various local businesses. Fig. 1 shows the layered architecture of VR-ZOCO, displaying its components and the actors interacting with these layers. The present work contributes to the development of the Input Layer, tasked with managing, among other responsibilities, user interaction with the platform and VR shopping spaces.

3.2. Motor limitations in people with spinal or brain damage

Hemiparesis and hemiplegia, resulting from injuries to the motor cortex or descending pathways, are the primary causes of motor dysfunction in the upper limbs following a stroke or spinal damage. These conditions manifest as weakness, spasticity, ataxia, and reduced sensitivity, impacting the mobility and dexterity of the arm, hand, and fingers.

In the arm, hemiparesis is characterized by overall weakness affecting flexion, extension, abduction, and rotation. Spasticity can cause stiffness, especially in flexion, limiting mobility and making activities such as reaching for objects or bringing the hand to the mouth difficult. Ataxia affects coordination and movement control, making actions imprecise and clumsy. Reduced sensitivity can affect proprioception and stereognosis, hindering arm and hand control in space.

Limitations in the hand are particularly relevant for interacting with objects and tools. Reduced grip strength, resulting from muscular weakness and spasticity, makes grasping and manipulating objects difficult. Diminished dexterity affects the ability to perform fine finger movements, such as pinching or writing. Tremor, present in some cases, can increase the difficulty of performing precise tasks. Spasticity and pain can affect finger mobility, limiting flexion, extension, and abduction. In more severe cases, deformities such as claw flexion or extension of the fingers can be observed, further limiting hand function.

Understanding these limitations is important for adapting the environment and interactions to each patient's conditions, enabling them to enjoy the use of new technologies that can shape the direction of society.

4. Adapted interaction mechanisms for VR shopping activities

The prototype we used as a basis for adapting the interactions discussed below was developed for Meta Quest devices, so we will use the options and features offered by Meta's API. This decision was motivated not only by Meta being one of the most established and successful companies in the field of VR but also by the years of development and continuous updates Meta performs to its API. Furthermore, Meta devices incorporate hand tracking, which allows the shopping experience to be closer to reality by using hands and, as shown in the Section 1, turns out to be easier than using controllers for people with reduced mobility in the upper limbs.

4.1. Interaction mechanisms for healthy users

We will begin by presenting the interaction mechanisms, available in the demo for users without upper limb problems, which were later adapted.

4.1.1. Navigation: teleporting and rotating

In a large virtual shopping environment, where various exhibitors are separated by some distance, navigation is essential. Such a shopping space allows for a larger product assortment, gamifies the environment, and creates a more attractive virtual space than simply presenting a single product exhibitor. To avoid the need for large physical spaces, it is very important to offer users ways to move around the environment without having to physically move. One of the most popular and commonly used navigation mechanisms in VR is teleportation, as it provides a quick and easy way to move through the environment while generally not inducing motion sickness [REDRF23].

Teleportation is a navigation method provided by Meta's API for the Unity game engine, which we are using to develop the VR application. The interactions offered by the API are based on states of components called *Interactors*, which are added to the input devices—in our case, the virtual hands—and *Interactables*, which are added to objects in the environment that we want the corresponding *Interactors* to interact with.

On the other hand, we have body rotation in virtual space. This allows rotating the user's view by a specific angle relative to the vertical world axis of the scene, simulating a turn without the user needing to physically rotate. While this option might seem less useful for a healthy person, for potential users who have suffered a stroke or any other incident that has forced them to use a wheelchair, this functionality is crucial for exploring a virtual space in 360º.

To initiate one of these hand interactions, Meta's API requires, in addition to configuring the corresponding objects in the Unity scene with the appropriate scripts, identifying a *hand pose*. The concept of *hand pose* is vital for adapting these component interactions:

- **Shape recognition**. It is based on a set of boolean conditions regarding the position of one or more fingers of the hand. When the data collected by the *hand tracking* meets these conditions, the shape is "activated". The boolean conditions are based on comparing the data obtained from *hand tracking* with defined *finger features*[†], which are specific positions of the fingers to define a shape. These are *curl*, *flexion*, *abduction*, and *opposition*. Thresholds are set to determine the transition from one feature to another.
- **Transform recognition**. The hand transform represents the orientation and position in 3D space of the hand. It is based on boolean conditions that must be met with respect to the fingers, wrist, and/or palm. For example, it can be checked if the palm of the hand is oriented upwards, downwards, if the fingers or wrist are oriented upwards, and many more alternatives.

[†] https://developer.oculus.com/documentation/unity/unity-isdk-hand-pose-detection/#finger-features

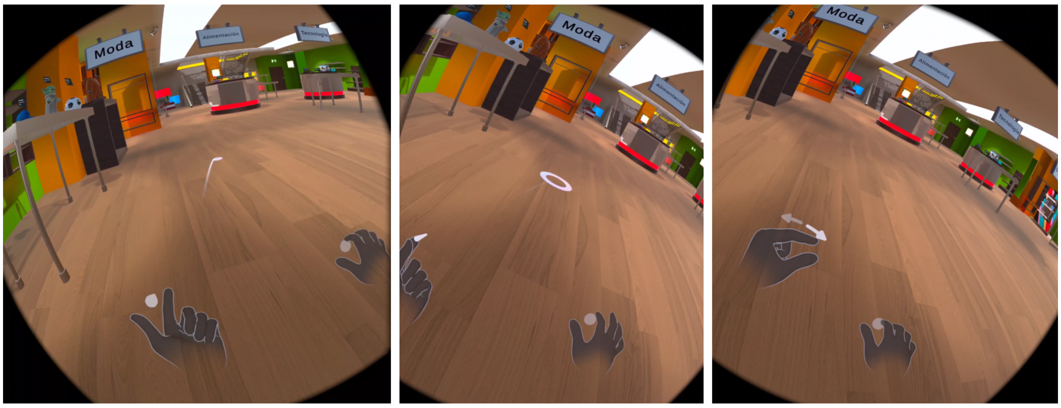

Figure 2: *Hand poses and actions required for teleporting and turning. Starting from the lefto f the image: (1) hand pose that invokes the arc to perform a teleportation, (2) pinch gestuer using thumb and index fingers to activate the teleportation, (3) turning interaction, which requires a pinch for activate it.*

Moreover, images captured using the *scrcpy* tool are shown to display these interactions in the unadapted environment. Please, note that the fish-eye-like effect shown is caused by the video streaming of the tool itself. Fig. 2 shows the hand poses that must be performed to invoke the possible initiation of a teleportation or rotation interaction. We will describe the images as they are shown from left to right. i) The L pose with the palm pointing upwards invokes the arc that allows aiming where the user wants to teleport, represented with a small circle the destination location. ii) Shows the action that activates teleportation when pointed to a place that allows teleporting, which consists of making the *pinch* gesture, joining the tips of the index finger and thumb. The circle indicating the destination becomes gradually taller as the *pinch* is performed. iii) Shows the hand pose necessary to invoke the arrows which, when selected with the same *pinch* described above, will rotate the user 45° (an adjustable angle) towards the side indicated by the selected arrow. It is noteworthy that, to avoid overlapping both invocations (the arc for teleportation and the arrows for rotation) and leading to errors, Meta's API offers as a gate or lock to choose one or the other, a minimum and maximum wrist rotation angle to select one interaction over the other. These angles for switching from one interaction to another can be modified.

4.1.2. Grabbing products

Grasping products is an essential interaction mechanism to allow users to fully explore products, rotating them, scaling them, or performing more complex actions like moving subparts of the same or detaching those subparts. The grasp, like any other interaction implemented by Meta's API, also relies on the *Interactor-Interactable* framework. In this case, the interaction requires that the hand be close to the object with the *Interactable* component and others, such as a Collider, necessary, and to perform a *pinch* gesture or a palmar grip. The latter consists of bringing the fingertips towards the palm of the hand. It is possible to allow grasping an object either with the *pinch*, with the palmar grip, or with both. While the *pinch* is detected through an advanced calculation of the API in which the grip strength and the fingers involved are taken into account, the palmar grip and its strength are based on the curl values of the fingers to detect whether there is a grip or not.

To release a grasped object, the thresholds established must be exceeded for the API to determine that a grip is no longer being performed. As a general rule, it is recommended to extend the fingers completely to facilitate this detection and perform the release of the grasped object. Fig. 3 shows an example of grasping and releasing objects in the prototype used as a base. A visual component that renders the hand's skeleton has been added to appreciate that, even though a *pinch* gesture is being performed to grasp, the API allows modifying the visual form of the hand to fit a specific shape and generate greater immersion. This is done through a series of components that allow modifying a hand pose in the Unity editor to use it with a certain object when grasping it.

4.1.3. Interacting with the shopping cart

In the virtual shopping space prototype, we opted to represent the shopping cart physically instead of using a proposal that represents an abstract shopping cart in the form of a user interface as in other works in the literature [SHD*18]. Although an abstract shopping cart can save screen space and require other interactions, such as pressing or selecting elements from a graphical interface, a physical shopping cart results in a more natural shopping experience. To avoid the user having to move the cart, it will follow the user.

To add or remove products from the cart, the object must be brought close enough into it until green particles appear, indicating to the user that the product has been added (see Fig. 4). This happens thanks to Unity's physics engine through collision detection. On the other hand, to remove objects from the cart, it is enough to take them out of it, and they will return to their initial position to be displayed again.

4.2. Adapted interaction mechanisms

In this subsection, we detail how we have adapted, in the most general way possible, the interaction mechanisms shown in Section

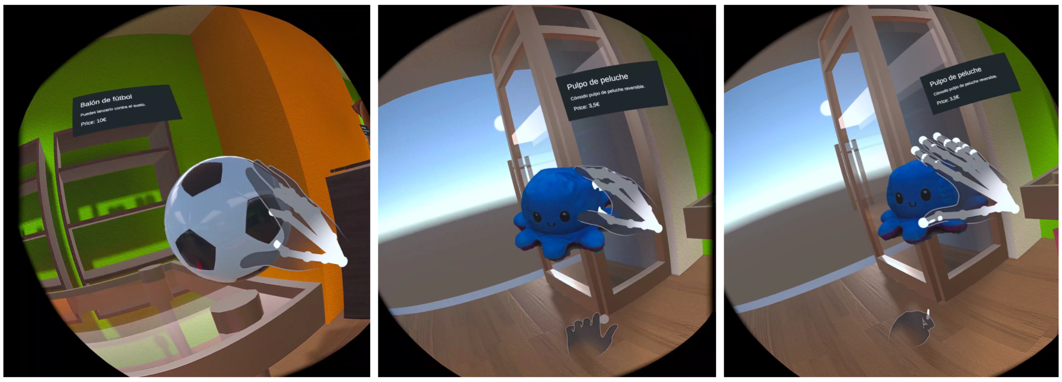

Figure 3: *Grabbing objects throguh pinch and releasing them.*

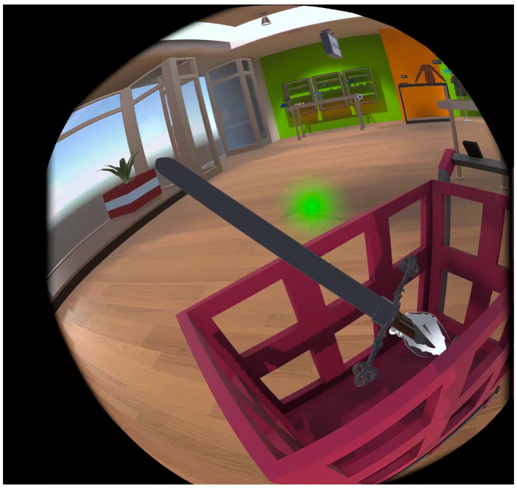

Figure 4: *Adding a product to the shopping cart.*

4.1. Starting from as generic a basis as possible, will allow us in the future to adjust, refine, and optimize adaptations based on the particular situation and limitations of each user. The adaptations to these interaction mechanisms have been carried out through the development of scripts in C#, the Unity editor, and calls to functionalities of Meta's API for Unity.

4.2.1. Adapted navigation mechanisms

We must consider the difficulty that people with reduced mobility in their upper limbs might face in performing *hand poses* due to the mobility of the fingers required. Given the conditions described in Section 3.2, articulating the fingers is a very difficult action due to the stiffness and limited strength in their upper limbs. Without being able to adapt navigation through virtual environments, such individuals would not be able to move through them, negatively affecting their experience. Therefore, thanks to Meta's API being based on interfaces, we can use a single component of *transform recognition* (see Section 4.1.1) that activates the arc for pointing where the user wants to teleport. Being aware that we must combine the wrist turning angle to indicate whether to activate the teleportation arc or the rotation arrows, we have opted for recognizing that the palm of the hand points towards the ceiling, not requiring flexing or extending the fingers. However, we are aware that the particular conditions of each user may vary, due to their ability or not to turn their wrist more or less, having to adapt in a more general way these invocations in the future.

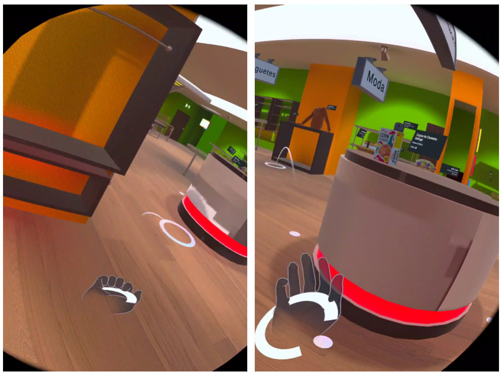

Figure 5: *Adapted teleportation that uses a circular sprite to show the time remaining for teleporting.*

Another obstacle for which it is necessary to adapt these invocations is the way to select or start the interaction. As shown in Section 4.1.1, both teleportation and rotation require performing a *pinch* to carry out both interactions. In the case of teleportation, we have decided that the user only needs to point to the site where they wish to teleport for 1.3 seconds, as can be seen in Fig. 5. In this case, the shape of the user's fingers is not considered, and they will only need to point the palm of the hand upwards to invoke the arc. Additionally, the lock to discern between activating the teleportation arc or the rotation arrows admits a certain angle of variation to avoid resetting the interaction due to tremors or other causes. Also, to avoid errors when pointing, the environment has been marked with small circles to indicate teleport points. These consist of an area that will cause the arc to snap to the indicated point, allowing for some error in aiming instead of only allowing that single circle. Also, we decided to add visual feedback in the form of a loading circle, which progresses until completion as the pointing time advances, to prevent them from stopping pointing too early and having to start over from scratch.

Figure 6: *Adapted turn showing the arrow that belongs to each hand.*

Lastly, regarding displacement by rotation, Fig. 6 shows how the invocations of the arrows for making turns have been adapted. As can be seen, the position and orientation of the hand are the same as in the non-adapted version, except that the minimum and maximum wrist rotation angles were altered. In this case, each hand now invokes a single arrow. Instead of performing the *pinch* gesture to execute the turn, the user will make a movement in the direction indicated by the arrow, either with the hand or the wrist. This offers flexibility in performing the interaction, originating a movement from the elbow or from the wrist itself, depending on the user's particularities. Each hand will take care of turning 45º in one direction or the other, which will be indicated by each arrow.

4.2.2. Adapted grab, distance grab and release of products

Grasping products requires exerting force with opposite fingers, the index and thumb to bring them together, or with the palm of the hand and the fingers towards it. We recall the stiffness and lack of strength that people with spinal cord or brain injuries have in their fingers. Based on these limitations, the product grasping has been modified through two different functionalities, one by modifying Meta's API and another through the development of a C# script. The modification of the API consists of adding calls to a method that modifies the grip strength, establishing new values for a series of parameters, such as the distance at which a grip is considered to start. Additionally, this method can also modify thresholds to determine when an object is released from a grip. The calls are included in a component that is added by default to the *HandGrabInteractor* components, responsible for managing grip interactions with the hands. This adaptation may help people with some mobility in their fingers to perform grips through the movements they can make.

On the other hand, these modifications may not be sufficient for people with more reduced mobility in their hands. Therefore, through a developed script, it is detected when the hand is over the surface of the object and, after 1 second, an automatic grip will be performed. Although it may seem simple, the *Interactor-Interactable* lifecycle must be taken into account, so it must be done by checking the states of the *Interactors* and *Interactables* to execute the automatic grip. Additionally, following this lifecycle allows for not losing functionalities like adapting the visual form of the virtual hand when a grip occurs as shown in Fig. 3.

Figure 7: *Adapted grab, including visual feedback.*

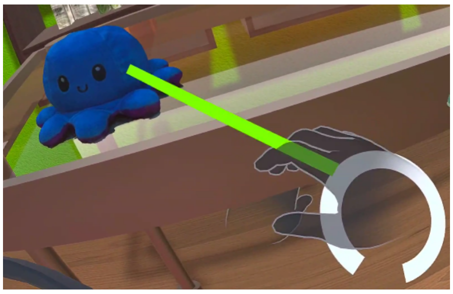

Figure 8: *Adapted distance grab.*

Fig. 7 shows, on the left, the state of the hand before initiating a grip, highlighting the outline in blue. Then, when performed, the outline turns green. This provides visual feedback to the user, thus knowing when a grip has occurred, whether performed automatically or not. On the other hand, Fig. 8 shows the implemented distance grip, based on *raycasting*. After pointing at an object at a certain minimum distance for 1.5 seconds, to which stretching the arm cannot reach, the object will travel towards the user's hand and perform a grip, as shown on the right side of Fig. 7. The origin of the ray comes from the MCP joint of the index finger, instead of another joint in which the user might have less mobility.

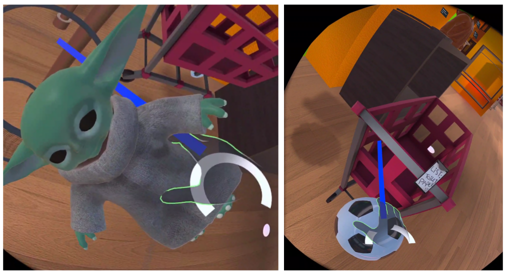

Figure 9: *Adapted object release and prodduct addition to the shopping cart.*

Lastly, we have the release of a grasped object. The solution we propose is to point to an object within the virtual environment,

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which follows the user and maintains a fixed distance and orientation to them so that it can be easily located. In this case, we opt for the recycling bin metaphor to free the hand of the selected object. This solution allows users to release grasped objects more precisely, as we must remember that not all users can exert enough force with their fingers for the hand tracking system to recognize that a grip has been released. The left image of Fig. 9 shows the ray that, after pointing for 2 seconds at the bin, will release the object and it will automatically move to its original position.

4.2.3. Adapted shopping cart interactions

Thanks to the added behavior in the shopping cart and the trash bin, which will follow the player and always stay by their side, the user can choose to add products to the cart either from a distance or by placing them into the cart if they can reach it. Considering that the limitations present in some users may pose an impediment to stretching out an arm and depositing the object in the cart, we have included the option of pointing at the cart for 2 seconds to add a grasped product to it. This can be seen in the right image of Fig. 9, where the color of the cast ray is blue and the circle is also used to indicate the progress of the pointing time.

5. Testing the adapted interaction mechanisms

In Section 4, we have shown the adaptation we have made using Meta's API for Unity of interaction mechanisms that can be used in VR-based shopping environments. However, we need to experiment with users who suffer from different restrictions in the mobility of their upper limbs to gather their feedback, verify that the design of the interactions is suitable for them to perform, and identify any necessary modifications to better adapt to each user.

Figure 10: *Volunteer student who suffered an ictus helping us to validate the adapted interaction mechanisms.*

An experimental session is planned at the National Paraplegics Hospital in Toledo (HNPT) with patients and therapists from that institution. Previously, we conducted a session with volunteer students from the faculty, who were healthy, to collect their feedback on the adapted mechanisms, as well as data that allow us to understand whether the design was appropriate or not. Additionally, we were able to count on a student with reduced mobility in the left half of his body due to a stroke. Thanks to his help, we were able to test the adapted interaction mechanisms with a person with such characteristics (see Fig. 10) and have an experience closer to what we will have in the HNPT. The healthy students did not use their fingers, so they acted as if they lacked mobility in them.

5.1. Methodology followed in the experimental session

First, the volunteers experimented with the application that did not have the adapted interaction mechanisms. They were asked to navigate to specific sections within the prototype and add the product they preferred to the cart. After completing these tasks, the changes made to the interaction mechanisms were explained to them before they could enter the application, while they were shown on the computer screen with practical examples how they should interact in the environment with the adapted interactions. Then, they were asked to perform the same tasks as in the unadapted environment.

After this, the feedback from the volunteers was collected, and the data from the interactions, obtained in both environments, were analyzed. The data are obtained thanks to scripts developed for this purpose, storing them in .csv files.

5.2. Data collected about navigation and product grabbing

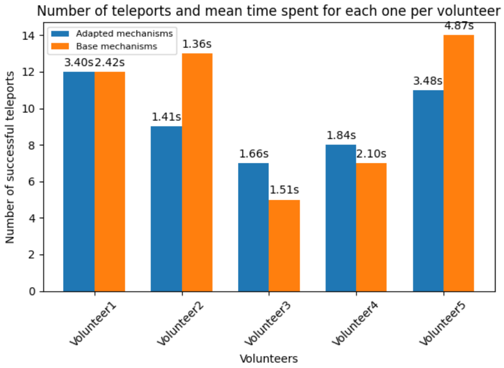

Figure 11: *Number of teleportations performed by each volunteer in each environment and the average time needed to perform each teleportation.*

We will analyze the data recorded in .csv files for each of the 5 volunteers, where "Volunteer5" is the volunteer who suffered a stroke, to observe if there were significant changes in behavior in the interactions. The student who suffered the stroke had to navigate in the unadapted environment with his right hand, as it was impossible for him to do so with the hand with reduced mobility, while in the adapted environment he used it as much as possible. We aim to verify if the adapted interaction mechanisms impaired the user experience, such as an increase in the average time they needed to teleport to a destination position, or if they interacted less with the products due to the adaptations made. Fig. 11 shows that there is no significant difference between the number of teleportations made by each volunteer nor in the average time required for each teleportation. Additionally, we must consider the 1.3 seconds of waiting time required to confirm the teleportation in the case of the adapted environment. We can appreciate that the volunteers did not show reluctance to navigate little, as 3 of them performed the same or even more teleportations. This, accompanied by the verification that the average time required to successfully teleport in the volunteers did not increase beyond 1.3 seconds, indicates that the experience with the adapted mechanism was similar to the unadapted mechanism. On the other hand, the precision of performing teleportations improved, as in the adapted environment, an average of 3.14 attempts were needed (i.e., pointing to another destination before performing a teleportation), while in the unadapted environment, 5.67 attempts were needed.

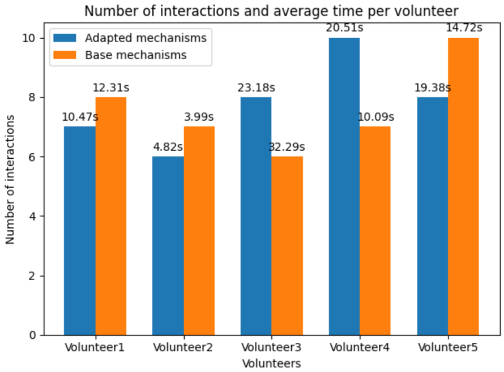

Figure 12: *Number of grips performed by each volunteer in each environment and the average time duration of each.*

Fig. 12 shows the number of grips made by each volunteer, the average duration of these in seconds. In 4 of the 5 volunteers, the grips were on average longer. This may be because they did not need to perform gestures like the *pinch* nor exert force to do them, making it comfortable for them to perform grips and inspect objects more closely. On the other hand, it can be observed that the adapted mechanism does not negatively affect the number of interactions performed. While 2 volunteers performed a higher number of grips with the adapted mechanisms, the rest performed about 15% less. Close to 40% of the grips performed by the volunteers were distance grips, mostly because they could not reach the products without leaning towards them. This made us realize the need to, in the future, adapt the height and distance of the points to which one can teleport, to offer greater ease of grip according to the reach with the arms and the height of the user.

5.3. Feedback provided

The characteristics about which we asked and were most interested in knowing the opinion of the volunteers were the i) comfort of the interactions, ii) how difficult they considered it was to perform them, and iii) if it was easy to interact with the trash bin and the shopping cart. We conducted three questions based on a Likert scale from 1 to 5, where 1 is the most negative response, for example, very uncomfortable interaction, 3 is the neutral response, and 5 is the most positive. For the 3 questions, the following averages were obtained: i) 4.4, ii) 4, iii) 4.4, indicating very favorable satisfaction from the volunteers regarding comfort with the adapted interactions. On the other hand, as already mentioned, they suggested improvements in the designs of the adaptations, such as including a visual element that indicated the progress of the interaction and knowing how much longer they needed to point, for example, to teleport. Additionally, having volunteers of different heights, two of them indicated that they felt low in relation to the product counters, making it difficult for them to directly reach objects.

6. Conclusion and future work

In this work, we have presented the adaptation, for people with reduced mobility in upper limbs, of a set of interaction mechanisms that can be used in VR Shopping environments. Specifically, our goal is to provide accessibility options, among which these adaptations would be found, on a VR and AI-based e-commerce platform called VR-ZOCO, to assist small businesses and local economies in the upcoming e-commerce revolution. We have described the enormous difficulty these people, who suffer from spinal cord or brain damage, have in exerting the necessary force, gestures, or other types of input method with their hands, in VR applications built with Meta's API for Unity. That is why, to offer these options and have them participate in the near future of e-commerce, we have designed a series of adaptations to interaction mechanisms such as grasping and releasing objects, navigation and body rotation, and adding products to a shopping cart. These general adaptations make use of Meta's API to avoid requiring users with limitations to perform extensions, abductions, or flexions of fingers or hands, which in some cases are impossible.

Prior to conducting an experimental session with patients and therapists from HNPT, we have presented the results of data obtained and the feedback from 5 volunteer students, who performed a series of shopping tasks in the environment without adapted mechanisms and in the one that had them adapted. The results showed that the average times of product grips for inspection were generally higher in the adapted environment, so these mechanisms did not constitute an impediment that was reflected with a shorter interaction time in most cases. The same occurred in the case of navigation, where, in the cases that required more average time by the volunteer, it did not increase by more than 1.3 seconds, the time the user needs to point to confirm the destination place. On the other hand, the volunteers provided very valuable feedback, such as the suggestion to include visual feedback to know the remaining time to perform an interaction.

From this point forward, we will work on growing the accessibility options to fit the limitations of each specific user. This may require a preliminary phase of recognition and calibration through a series of movements or actions, which allow the application to detect, for example, maximum and minimum wrist rotation angles to configure these according to the user's conditions. Additionally, other options that adapt to the user can be the height at which to locate shelves and objects on them, so that people of different heights have similar experiences regardless of this aspect. Moreover, this will allow people who cannot bend to reach certain objects to have them within their reach.

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