Studying Natural Human-computer Interaction in Immersive Virtual Reality: A Comparison between Actions in the Peripersonal and in the Near-action Space

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Abstract: Interacting in immersive virtual reality is a challenging and open issue in human-computer interaction. Here, we describe a system to evaluate the performance of a low-cost setup, which has not the need of wearing devices to manipulate virtual objects. In particular, we consider the Leap Motion device and we assess its performance into two situations: reaching and grasp in the *peripersonal space*, and in the *near-action space*, i.e. when a user stays on foot and can move his own arms to reach objects on a desk. We show how these two situations are similar in terms of user performance, thus indicating a possible use of such device in a wide range of reaching tasks in immersive virtual reality.

1 INTRODUCTION

In the last decade, virtual reality (VR) has had a widespread success, thanks to the release of several head-mounted displays (HMDs), such as the Oculus Rift or the GearVR (by OculusVR), the HTC Vive, the Project Morpheus (by Sony) or the Google Cardboard. These new technologies can be considered low cost if compared to the ones previously available, for example expensive motion capture systems or room-filling technologies, such as the CAVE. In the past, because of the high cost of the hardware required, VR was mainly used for military applications, cinema and multimedia production. Nowadays, instead, it has become very popular in the entertainment world and has caught the attention of researchers who are studying its application in many other different fields: serious games and edutainment, cognitive and physical rehabilitation, support for surgeons in diagnosis, operation planning and minimal invasive surgery, modeling and products design, assembly and prototyping process, cultural heritage applications.

The work presented in this paper is a preliminary study, mainly focused on analyzing interaction modalities within immersive virtual reality. In fact, in many cases, controllers or joysticks are used to interact with the virtual environments. Even if this solution is effective, actions performed do not resemble to their real counterpart: people do not push buttons to grab objects in their daily life. Therefore, non-wearable devices could be an alternative solution. In particular, the Leap Motion, a hand tracker device, allowing the user to interact with virtual objects without wearing specific tools and to see a virtual representation of his hands, seems to be promising. A recent study (Sportillo et al., 2017), compared a controller-based interface with a realistic interface, composed by a steering wheel and the Leap Motion, in a driving simulation application. People reaction time was lower in the first case but a better control over the vehicle and a higher stability was measured in the second case. Moreover, (Khundam, 2015; Zhang et al., 2017) implemented a walk-through algorithm for navigating the virtual environment based on hand-gesture detection. Performances were task-dependent, but participants preferred the Leap Motion to traditional gamepads and joysticks, stating it is more intuitive, easier to learn and use, causes less fatigue and motion sickness and induces more immersion. Despite its tracking issues, researchers are very interested in the application of the Leap Motion for different purposes: simulation of experiments (Wozniak et al., 2016) or oral and maxillofacial surgery (Pulijala et al., 2017), gaming, from puzzle (Cheng et al., 2015) to First Person Shooter (Chastine et al., 2013), model crafting (Park et al., 2017) and visualization of complex

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dataset (Reddivari et al., 2017; Cordeil et al., 2017).
In this paper, we aim to assess the stability, efficiency and naturalness of a Leap Motion-based interface during the interaction with virtual objects in the *peripersonal* and *near-action space*. We define as *peripersonal space* the area reachable by an user sitting in front of the game area; whereas we define as *near-action space* the area in which the user can reach objects standing in front of the workspace and performing few body movements (not walking).

2 RELATED WORKS

The success of virtual reality and HMDs is correlated with the fact that these low cost technologies are still able to provide a truly immersive experience (Chessa et al., 2016) and an intuitive human-computer interface.
Headset like the Oculus Rift and the HTC Vive also provide simple tracking systems, able to localize and track the HMD in a limited area. Moreover, these commercial systems offer better performance, higher resolution and lower weight with respect to expensive specialized hardware (Young et al., 2014). Conversely, they tend to cause simulator sickness. Anyway, it is also important taking into account that, while the HTC Vive is conceived as a room-scale device, the Oculus Rift is mainly suggested for seated or standing scenarios (Cuervo, 2017). A recent study compared the two HMDs in a Pick-and-Place task and pointed out that the HTC Vive tracking system is more reliable and stable than the Oculus one, while there is no difference in term of precision (Sužnjević et al., 2017).
In order to guarantee a natural interaction, it is also fundamental considering the reliability and precision of the Leap Motion device. Its stated accuracy is 1/100th of a millimeter in a range from 25 to 600 mm above the device. Anyway, it has been demonstrated that in static scenarios (not moving hands), the error in measurement is between 0.5 mm and 0.2 mm, depending on the plane and on the hand-device distance; while in dynamic situations (moving hands), independently from the plane, an average accuracy of 1.2 mm could be obtained (Weichert et al., 2013). To our knowledge, no study on the Leap Motion accuracy has been conducted yet with the device mounted on a HMD. Anyway, for our purpose, we can consider the hand tracker device reliable enough.
Finally, an issue with which everyone trying to recreate a natural hand-based interaction with virtual environment deals with is the hand-object interpenetration due to the absence of real physical constraints between the virtual hand and the virtual object. Different grasping approaches has been investigated: using a 3D model which simply follows the real hand and can interpenetrate objects; a see-through method, similar to the previous one, but showing the actual position of the fingers inside the objects; using a hand model constrained to avoid interpenetration; using two hands, a visual one not interpenetrating objects and a ghost hand directly following the real one; using different kind of feedback during collision, such as visual (object or fingers changing color), haptic (pressure, vibration) or auditory feedback.
Many studies have pointed out that even if people prefer interpenetration to be prevented, actually this method does not improve performances, while any kind of feedback seems to be a promising solution (Prachyabrued and Borst, 2012; Prachyabrued and Borst, 2014; Just et al., 2016).

3 MATERIALS AND METHODS

3.1 Hardware Components

The experimental setup is composed of a head-mounted display, the Oculus Rift DK2[1], with its own positional tracking camera, and a computer able to support VR. For the interaction with virtual objects, we used the Leap Motion[2] mounted on the HMD.
The Oculus Rift DK2 has a 2160×1200 low-persistence OLED display with a 90-Hz refresh rate and vertical and horizontal field of view (FOV) of maximum 100 degrees (Figure 1b). This headset contains a gyroscope, an accelerometer and a magnetometer, which allow to calculate user's head rotation in the three-dimensional space and consequently to synchronize his perspective in the virtual environment in real-time.
Moreover, the Oculus Rift provides a 6-degree-of-freedom position tracking system: the Oculus Sensor device is an infrared camera able to detect and track the array of infrared micro-LEDs on the HMD surface. In this way, it is possible to obtain a precise 3D position estimation and tracking of the user head in the 3D space. The tracking area, however, is defined by the limited field of view of the camera (Figure 2).
Another important element of our setup is the Leap Motion. It is composed by two cameras and three infrared LEDs that allow to detect hands inside a hemispheric area of approximately 1 meter above the device. Originally conceived for desktop applications,

[1] https://www.oculus.com/
[2] https://www.leapmotion.com/

Leap Motion has been recently adapted for VR applications: a special support for the device to be placed at the centre of the frontal part of the HMD (Figure 1a) is supplied and on the web site it is possible to freely download an integration software for the development of VR contents, the Orion Beta. In our case, we used the 3.2.0 version.

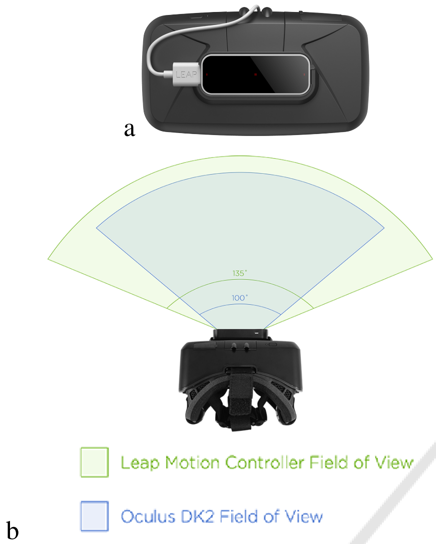
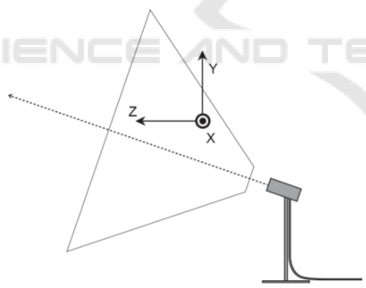


Figure 1: (a) Leap Motion device mounted on the Oculus Rift DK2 (b) FOV of the Oculus Rift and of the Leap Motion device.



Field	Type	Typical Value
CameraFrustumHFovInRadians	float	1.292 radians (74 degrees)
CameraFrustumVFovInRadians	float	0.942 radians (54 degrees)
CameraFrustumNearZInMeters	float	0.4m
CameraFrustumFarZInMeters	float	2.5m

Figure 2: Field of view of the Positional Tracking Camera of the Oculus Rift.

Finally, the computer we used respects the minimum requirements for both the Oculus Rift and the Leap Motion. It is an Alienware Aurora R5 with a 4GHz Intel Core i7-6700K processor, 16GB DDR4 RAM and a Nvidia GeForce GTX 1080 (8GB GDDR5X RAM) graphics card.

3.2 Software Components

The VR environment has been created using Unity 3D version 5.6.1f1. Unity 3D is one of the most used game engine for the creation of games and 3D and 2D contents. In order to integrate the Oculus Rift and the Leap Motion with Unity, we used the specific integration packages, respectively the Oculus Utilities and the Leap Motion Unity Asset Core and Modules, available on the official sites of the two devices.

3.3 Subjects

21 people, 12 males and 9 females, aged between 24 and 52 (mean 30,8 $\pm$ 6,7 years) took part to the experimental session. All the participants were volunteer and received no reward. The majority of them had already tried the Leap Motion and VR devices and applications in the past, but only 4 of them had already tried the Oculus Rift.

3.4 Interaction Task

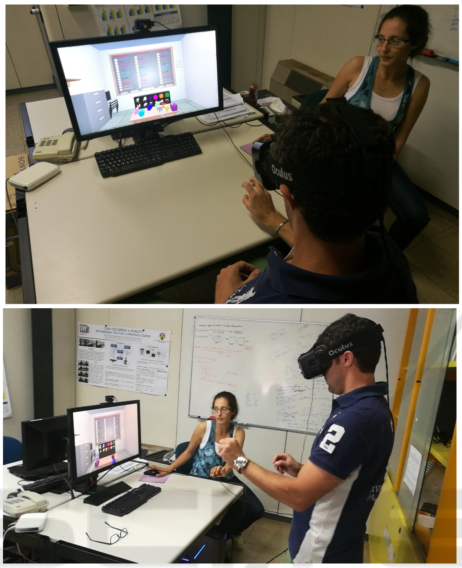
As our main purpose is investigating the operability limits deriving from the combination of the Leap Motion and the Oculus Rift when interacting with virtual objects, the task is very simple so that performances are related mainly on the interaction than on the level of difficulty of the task itself.

Participants wear the Oculus Rift and act in a virtual room. Right in front of them, there is a virtual desk, corresponding to the real desk in position and dimension, while behind them a virtual bookcase, corresponding to the real one, delimits the game area (Figure 3). The position of these elements is defined in the reference system of the tracking camera, which is considered the origin of our virtual environment. The camera, in fact, is the only fixed point in our setup, existing in both realities, the real one and the virtual one, and the position and rotation of the headset in the 3D space is referred to the system of reference of the camera. When the Oculus Rift is out of the boundaries of the camera FOV, lags occurred in the rendering of the scene. When this happens, red lines, representing the camera tracking cone, are displayed so that the player can understand the reason of the problem and come back to the tracked area.

On the desk there are 12 objects, different in color and shape, and players are asked to grab them, one per time and using a single hand, and place them in the corresponding hole in the black support behind.

A desktop application, showing the scene from a fixed point of view, allows an external operator, the supervisor, to see what the player is doing and help him in three ways: deleting some objects in order to make the scene clearer; repositioning objects accidentally thrown out of the game area; selecting a hole. The operator will also be able to reset the scene, start the timer for the acquisitions and stop it.

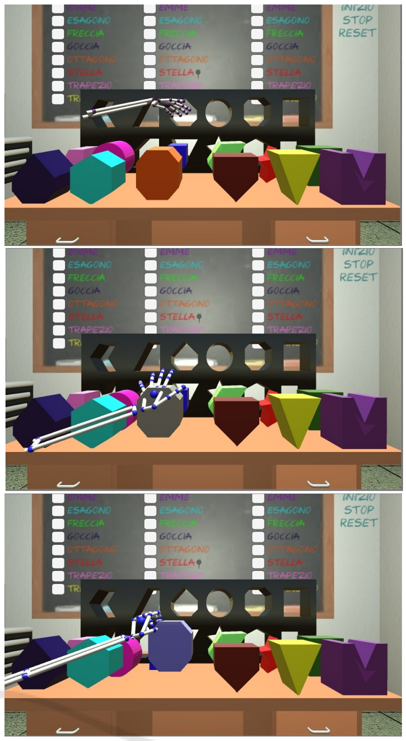
As in a pilot study, in a task of grabbing and dragging objects in the *near-action space*, participants complained about the instability of the hands tracking, which caused inadequate performances, we have decided to write our own grasp function instead of using the one provided in the Leap Motion Interaction Module. Moreover, we have decided to create two slightly different versions of the game, one with the interactable virtual objects in the *peripersonal space* and one with the objects in the *near-action space*. In the first case, the game area corresponds almost to the real desk 110 cm long and 60 cm wide and the volunteer sits on the chair; in the second case, instead, the game area occupies part of the real desk and the space between the desk and the bookcase, for a total surface 156 cm long and 140 cm wide and the participant has to stand up and play on foot (Figure 3). The two setups have been created in order to understand whether low performances, previously obtained in the pilot study, were due to the algorithm used to interact with virtual objects or to Leap Motion tracking issues in a *near-action space* interaction. Concerning the grasp function, every time a hand collides



a

b

Figure 3: Example of the two different setups with the main user immersed in the virtual reality and an external operator supervising him: (a) *Peripersonal space* setup (b) *Near-action space* setup.



a

b

c

Figure 4: Grasp function: (a) The user looks at the scene (b) The user reaches an object (c) The user grabs an object.

with an object, the object itself turns grey (Figure 4b) and the distance between the palm and the center of the object is calculated. We then check the hand's Grab Angle, which is a precalculated value, and, in case it is greater than a threshold experimentally defined, the object becomes purple (Figure 4c) and its new position is calculated so that the distance between hand and object remains constant; if the Grab Angle is smaller than the threshold, no changes are applied to the object. The most correct way to grasp an object is approaching it with the hand open and closes it until the object changes color. While, in order to release the object, the user has to open his hand and move it away from the item.

In order to ensure a greater stability, we also decided not to implement a realistic physics. For example, when an object is not colliding with the hand, its position and rotation is locked. On one hand, this causes the presence of objects floating in the air; on the other hand, it is the simplest way to overcome one of the most common mistakes users do while using the Leap Motion: grabbing an object and looking around for the right hole. In fact, the rotation of the head causes the hand to get out of the edges of the Leap Motion FOV (Figure 1b), which can potentially lead to an unstable behavior of the object grabbed.

3.5 Experimental Parameters

The evaluation of the performances is divided in 3 different parts: (i)*objective parameters* recorded during the game execution; (ii) the *Simulator Sickness Questionnaire*; (iii) the *user's subjective opinion*.

3.5.1 Objective Parameters

During the task execution, for each participant, we measured the total time required to complete the task and the average time required to position each single object. As the task is very simple, we expect that these values reflect the stability and efficiency of the human-computer interaction modality used, only. Moreover, we counted the number of errors, in terms of repositioned or deleted pieces, selection and reset actions. If the system is stable, then participants will not need any external aid.

3.5.2 Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) is the standard test commonly used when working with virtual reality. It allows to analyze the participants' status before and after each exposure to VR in order to estimate if the experience inside a virtual environment had some physical effects. It considers 16 different aspects: general discomfort, fatigue, headache, eye strain, blurred vision, dizziness with eyes opened or closed, difficulty focusing or concentrating, fullness of head, vertigo, sweating, salivation increase, nausea, stomach awareness, burping. These symptoms indicate a state of malaise due to a poor quality of the rendering of the virtual environment or to a too slow integration of signals coming from different sensors or to a bad tracking leading to a delay between visual information coming from the HMD and other information coming from other sensory channels (vestibular, proprioceptive). The user has to rate these voices using a scale ranging from 0 to 4, where 0 is none and 4 is severe.

3.5.3 Subjective Opinion

In order to evaluate the user's experience we wrote a custom questionnaire, taking into account different aspect related to the interaction of the user in VR. First of all, it is important to understand his/her degree of confidence in moving in a virtual environment, unable to see the real obstacles surrounding him (real desk and bookcase). Then, we are interested in investigating at what extent movements performed are perceived as natural and intuitive or, otherwise, at what extent the user has to adapt to the system in order to interact with virtual objects. Also, the obligation of using one hand could be perceived as a constraint, even if in general people unconsciously use only their dominant hand to perform a task. For this reason, we would like to receive feedbacks from the users. Moreover, we want to understand if our grasp function is efficient and stable enough, so that people can easily complete the task. Finally, it is important to know if visual feedback provides helpful information.

We ask participants to evaluate their experience in the two different setups and give a preference. The questionnaire, as shown below, is composed by an open question and eight 5-point Likert scale questions:

Q1) Did you prefer the peripersonal space or the near-action space trial? Why?

Q2) Did you feel safe to freely move your hands in the peripersonal space trial?

Q3) Did you feel safe to freely move your hands in the near-action space trial?

Q4) Was the interaction natural in the peripersonal space trial?

Q5) Was the interaction natural in the near-action space trial?

Q6) Level of frustration in the peripersonal space trial

Q7) Level of frustration in the near-action space trial

Q8) In the task, you could use just a hand, did this fact limit you?

Q9) Did the change in color of reached/grabbed objects help you?

3.6 Experimental Procedure

The experiment was composed of two trials: the *peripersonal space* setup and the *near-action space* setup. The order of execution was arbitrarily chosen by the experimenter: to reduce the statistical variability half of the participants carried out the first task in the *peripersonal space* setup and half in the *near-action space* setup. Before entering the main scene and starting the experiment, each participant can explore and act in a demo scene, in order to become familiar with the virtual scene and the interaction modality and find the boundaries of the game area.

First, participants were asked to submit the SSQ, in order to obtain an evaluation of their physical status before the exposure to VR.

Then, they had to perform the task in one of the two modality. When all the 12 objects were correctly positioned, the trial ended.

After this, the subjects had to submit a second SSQ, which was used both to evaluate users' status after the first exposure and before the second exposure to

the VR. The second trial was executed in the complementary modality to the one used during the previous task. In the two VR scenes the position of the objects changed, to avoid learning.
Subsequently, the users had to submit two last questionnaires: another SSQ and the subjective questionnaire.

4 RESULTS

4.1 Objective Parameters

The objective parameters defined to evaluate the performances have been analyzed on four levels: firstly, we made a general comparison between the results obtained in the first and second trial, without taking into account the setup; then, we compared the performances in the two different setups; after this, we made a "crossed" comparison considering the order of execution and the setup; finally, we considered the personal preference and the setup.
In each analysis the statistical significance of the differences between dataset was calculated by making a t-test analysis.
Dividing the data according to the order of execution and comparing the mean total completion times (Table 1), a consistent improvement of performances between first (mean 89,7 $\pm$ 26,4 s) and second trial (mean 73,3 $\pm$ 16,8 s) emerges. This is the only result statistically significant and can be explained as the learning curve of participants. These results are confirmed by the analysis of the completion time in the crossed comparison between the order of execution and the setup (Table 3).
Slightly better performances in terms of total completion time, have been found in the *near-action space* setup with respect to the *peripersonal space* setup, but this results is not statistically significant (Table 2).

Table 1: Mean and standard deviation of total completion time over all participants in the first and second trial (* means a statistically significant difference, $p < 0.02$).

	First vs Second trial	
	First	Second
Mean [s]	89,7*	73,3*
Std [s]	26,4*	16,8*

There is no correlation between preferences and performance, in fact, even if who preferred the *near-action space* setup shows better results in the near-action trial, this is not true for the one who preferred the *peripersonal space* setup (Table 4). Anyway the high variability suggests that more acquisitions are

Table 2: Mean and standard deviation of total completion time over all participants in the *peripersonal space* and *near-action space* setup.

	Peripersonal vs *Near-Action Space*	
	Peripersonal	*Near-Action*
Mean [s]	82	81,1
Std [s]	25,7	21,4

Table 3: Mean and standard deviation of total completion time over all participants considering the order of execution and the setup (P= *Peripersonal*, NA= *Near-Action*).

	Order and Setup Crossed Comparison			
	1^{st} P	2^{nd} P	1^{st} NA	2^{nd} NA
Mean[s]	94,8	67,9	84,1	78,3
Std [s]	27,5	14	25,5	17,8

required. Data on partial times confirm previous results. In all the experiments the only kind of help that the supervisor needed to use was the repositioning of objects but the mean related to this parameter was smaller than 0.5 in all the four analysis. Even if this result is not statistically significant it demonstrates the stability and reliability of our system. The absence of statistical significance in the different sets of data can indicate that the two setups can be considered equivalent.

4.2 Simulator Sickness Questionnaire

The SSQ analysis highlights no change in the physical status of participants as there are no significant differences between the data acquired before and after each task execution (see Fig. 5). 3 people however, reported a strange behavior of the system: in the *peripersonal space* setup, when rotating their head looking at the table, they perceived an oscillatory movement accompanied by a sort of zooming effect. This did not happen when they were staring at their hands while rotating the head. This phenomenon however did not interfere with their performances nor caused sickness.

4.3 Subjective Opinion

The subjective questionnaire allows us to know participants' opinions about their experience in VR and their interaction with virtual objects (see Fig. 6).

4 of the volunteers had not a preference and were satisfied by both the setups. 11 of them stated that they preferred the *near-action space* setup, but reasons were different: some of them said that it was more comfortable, as it allowed more freedom of movements and more interaction with the scene and

Table 4: Mean and standard deviation of total completion time (sec) over all participants considering the preference and the setup (P-P = preference *peripersonal - peripersonal* setup, P-NA = preference *peripersonal -near-action* setup, NA-P = preference *near-action - peripersonal* setup, NA-NA = preference *near-action - near-action* setup).

	Preference and Setup Crossed Comparison			
	P-P	P-NA	NA-P	NA-NA
Mean	97,6	93,5	73,9	77,8
Std	36,1	24,6	16,1	20,6

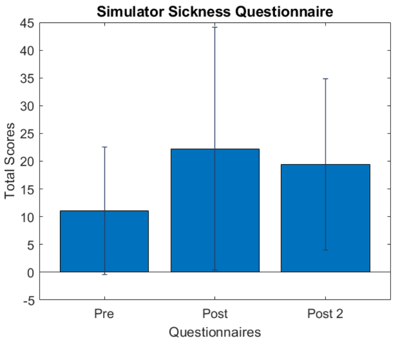


Figure 5: Mean and standard deviation of the Simulator Sickness Questionnaires submitted before the first trial (Pre), between the first and the second trial (Post) and after the second trial (Post 2).

the virtual objects and consequently the task was funnier and more engaging; other people referred that it was more realistic regarding distances. 6 of the participants judged the *peripersonal space* setup the best one, as they felt safer, more at ease and free to move and complained that in the other setup they felt constrained by the wires and the limited game area. Because of the FOV of Oculus camera, in fact, the game area is small. Moreover, on the boundaries, the Oculus tracking system frequently lost the signal from the HMD, this caused a lag on the rendering of the scene,

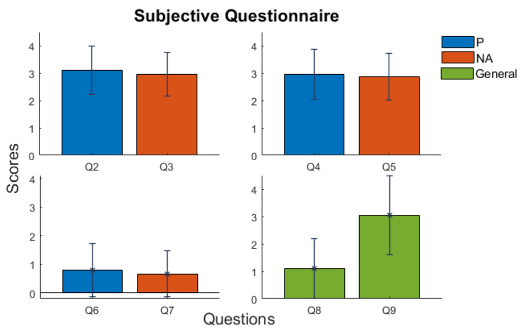


Figure 6: Mean and standard deviation of the answers given to the 8 5-points questions in the subjective opinion questionnaire. P = *peripersonal space* setup, NA = *near-action space* setup, General = questions not referred to a specific setup.

which was perceived as annoying and confusing. The same problem occurred when users rotated too much their head or looked backward, as there are no infrared sensors on the back part of the headset. All these factors influenced the rate given to questions Q2, Q3, Q4, Q5, which can be considered discrete to good. On one hand, in the *peripersonal space* setup, due to the characteristic of the setup itself, people felt their movements were limited, but the tracking was stable; on the other hand, in the *near-action space* setup, they felt freer to move in a larger space but were limited by the tracking system. Focusing on the naturalness of the interaction, instead, the absence of physics was perceived as weird and contributed to lower evaluations.

The interdiction of using both hands together to grab objects had a minimal influence (Q8), also because in general people tend to instinctively use just their dominant hand to move items, even in the real world. Regarding the interaction with virtual objects and the ability to complete the task (Q6, Q7), participants gave very good rates. So we can say that our grasp function was well implemented. Finally, the visual feedback (Q9) was appreciate, especially by those who had stability problem with the Leap Motion tracking, probably caused by too fast movements or interference within the sensors of the different devices.

5 CONCLUSIONS

Our work aimed to define a room-scale setup to be used when working with the Oculus Rift and the Leap Motion mounted on it. For this purpose, we have to take into account the limited field of view of the tracking camera, which causes the game area to be smaller than the one guaranteed by other tracking systems commonly used for the VR. Anyway, we were interested in finding the actual limits of the two devices and in assessing how people could feel constrained by them and if it is possible to create an engaging exergame even in a restricted space. From the received feedbacks, we can state that people in general prefer having more freedom of movement and just the fact of staying on foot satisfied them. The experience is even more pleasurable and engaging when the player is far from the boundaries of the game area, where tracking is less stable: it has frequently happened that participants had to find alternative strategies in order to reach certain objects still remaining in the limits of the camera FOV, for example stretching their left arm (for right-handed people). These situations in which the user is forced to adapt reduce the naturalness of the interaction and the sense of presence. Moreover, we wanted to evaluate if our grasp function could allow a natural and efficient interaction with virtual objects. Many participants also reported that the possibility to see a virtual representation of their hands and use them to interact with the surrounding environment, made them feel more confident, as it enhanced their capability to estimate distances. Anyway, further investigations on this topic are required. One of the main aspects that people pointed out was the absence of physics rules, so it would be interesting to investigate how to add gravity or collision between objects without losing stability. Finally, we would like to refine the parameter controlling the grasp action and adapt it to the shape of different objects. This could also potentially solve the object-hand interpenetrating problem still maintaining good performances.

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