IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received September 15, 2017, accepted November 9, 2017, date of publication December 11, 2017,
date of current version March 9, 2018.

Digital Object Identifier 10.1109/ACCESS.2017.2782254

Evaluation of Presence in Virtual Environments: Haptic Vest and User's Haptic Skills

GONZALO GARCÍA-VALLE, MANUEL FERRE, (Member, IEEE), JOSE BREÑOSA, AND DAVID VARGAS
Centre for Automation and Robotics, UPM-CSIC, 28006 Madrid, Spain

Corresponding author: Gonzalo García-Valle (gonzalo.gvalle@upm.es)

This work was partially supported by EC through AUGGMED Project (Project ID: 653590) under Grant H2020-FCT-07-2015.

ABSTRACT This paper presents the integration of a haptic vest with a multimodal virtual environment, consisting of video, audio, and haptic feedback, with the main objective of determining how users, who interact with the virtual environment, benefit from tactile and thermal stimuli provided by the haptic vest. Some experiments are performed using a game application of a train station after an explosion. The participants of this experiment have to move inside the environment, while receiving several stimuli to check if any improvement in presence or realism in that environment is reflected on the vest. This is done by comparing the experimental results with those similar scenarios, obtained without haptic feedback. These experiments are carried out by three groups of participants who are classified on the basis of their experience in haptics and virtual reality devices. Some differences among the groups have been found, which can be related to the levels of realism and synchronization of all the elements in the multimodal environment that fulfill the expectations and maximum satisfaction level. According to the participants in the experiment, two different levels of requirements are to be defined by the system to comply with the expectations of professional and conventional users.

INDEX TERMS Haptic interfaces, human factors, serious game, thermal actuators, vibrotactile actuators, virtual reality.

I. INTRODUCTION

After several years of research, not only a Virtual Environment (VE), similar to real environment can now be perceived, but also complete immersion inside the environment can be felt, perceiving all possible stimuli through all body senses. In a way, we are in the 'virtual reality time' [1]. The aim of VE is to achieve the best user experience by improving realism or sense of presence, in such a way that the user feels full integration inside the VE. Advances in virtual reality (VR) technologies have led to creating realistic VEs, thereby making systems surprisingly realistic [2]. Likewise, many VR-oriented haptic devices have been developed since 90's [3], [4], but the failure in taking them to the general public has hindered their improvement. The evolution of VR technologies has led to the creation of many innovative applications that allow interaction with VR [5]–[7].

This paper presents the use of a haptic vest to perceive VEs by using two kinds of stimuli: tactile and thermal [8]. Therefore, the vest includes two kinds of actuators: (i) vibrotactile actuators to create tactile stimuli through vibration patterns, which simulate virtual interactions such as the contact with people or objects inside the VE; (ii) thermoelectric actuators, to create hot and cold sensations, so that the users perceive a change in temperature whenever they approach a thermal focus. The haptic patterns must be recognizable and similar to real interactions, looking for sensations as realistic as possible. Then, the ultimate objective is to improve the realism and the immersion or sense of presence through haptic perception, achieving experience that is much similar to reality by including both tactile stimuli.

The participants of the experiment have been classified into three groups: Haptic Experts (HE), Technology Experts (TE) and Non-Experts (NE). The paper presents the differences found among these three groups in their perception of a VE, in terms of realism, immersion and presence when haptic devices are included. Some experiments have been performed to evaluate the vest and the benefits of its inclusion inside a VR system.

It is important to relate the concepts of realism and presence. Realism is related to some technical aspects, such as high quality computer graphics or the amount and quality of stimuli that users receive from the VE [9], whereas presence is considered as the sensation of being physically present in a virtual place, with ability to interact with it [10], [11]. The definition given here for presence is a modified version of the one originally given by Minsky [12]. It is also important discriminate between immersion and presence, because immersion is described as an objective experience that is dependent on some technical characteristics [13]. Going by the definition per se, the increase in system realism can generate improvement in the sense of presence inside the VE [10]. Therefore, haptic vest can be considered an appropriate tool to increase realism, enabling perception of virtual elements more realistically in order to increase presence. Therefore, a questionnaire has been formulated to analyze haptic stimuli, based on the answers given by the participants, and ascertain whether the haptic vest can increase realism and sense of presence in a VE.

VEs are usually composed of a visual system in which most of the virtual stimuli are perceived. Moreover, practically in every case, the VE has an associated audio system that allows perceiving every sound produced in the environment. The next step in achieving a complete interaction with the system is integrating haptic devices, getting multimodal environments using most of the senses and approaching realistic VEs. High quality computer graphics is the basic requirement for creating a multimodal system, because aural haptic stimuli must be properly synchronized with the system. Besides, the spatial origins of the stimuli have to be coherent with the VE, to achieve a quality immersion in the virtual system [14]. To achieve the greatest presence inside the system and to verify if the developed haptic device has improved the performance of the VE, this study has considered an environment that involved three senses: vision, audio and haptics.

The outline of this paper is as follows: Chapter II describes the related work; Chapter III introduces the haptic vest developed for the VE; Chapter IV describes the serious game application and the devices used for the experiments; Chapter V presents the experimental procedures, the questionnaire and the details of the participants involved in the experiments, etc.; Chapter VI presents the experimental results; Chapter VII discusses the results and finally, Chapter VIII sums up the main conclusions drawn from this study.

II. RELATED WORK

The literature includes diverse types of studies on improving the realism of VEs. Some studies prove that high quality computer graphics produce better realism and thus better experience and improved performance [15]. It has been reported that adding more stimuli (aural or haptic), results in improving realism, because the users interact with the VE through senses [16]. Some works compare and demonstrate how better performances could be obtained with multimodal environments (audio-visual, visual-haptic or visual-audio-haptic systems) than with unimodal environments [17], [18]. Generally, multimodal interaction implies improvement in the sense of presence, by attending to the answers given by the participants of the experiment to the questionnaire [19], [20]. Many works have demonstrated how haptic interaction improves the performance of VE interactions [21], perceiving the VE more realistically through touch, e.g., feeling virtual textures [15], [16] or the handled tissues during a robotic surgery [22]. Several types of gloves, platforms [23] and surfaces [24] have been developed, which are greatly useful in VR applications.

As regards haptic vests, most of the previous developments and most of them were oriented toward applications relating to navigation in unknown environments, guidance or object detection [25]–[27]. Those developments were based usually on vibrotactile stimulation, although more sophisticated methods, involving the use of shaped-memory alloys (SMA) or thermal actuators [25], were also used. Moreover, some serious games, using haptic devices, were focused on learning or training purposes, by combining stimuli to improve realism, immersion or sense of presence in VEs. Those improvements benefited the objectives of the game (learning or training) by enhancing the similarities with the real scenario. The haptic vest used for tactical training [28] and the applications oriented toward medicine [29], rehabilitation [30] or student learning [31] are some of the examples that can be cited in this regard.

Finally, haptic vibration patterns are a key factor for improving realism in haptic interaction. These patterns are usually programmed, based on vibration sequences that orient the users inside a VE. The program indicates how to interact [32], [33] or associate particular patterns with events to improve task performance [34]. Moreover, those patterns have been tested, and their usefulness verified in transmitting information [35], mostly over upper limbs [33]. The objective of this study is to create haptic patterns by using the usual parameters and the patterns created must be reproducible over the user's trunk, as realistically as possible [36], [37].

III. HAPTIC VEST DESCRIPTION

The haptic vest is a device that generates tactile and thermal stimulation over the users due to interactions with a VE. This stimulation is generated through vibrotactile and thermal actuators distributed over different areas of the torso and the back of the vest. Figure 1 shows the front and the rear views of the haptic vest.

The vest has to be so tightly fitted to the user's body, so that all the actuators remain in contact with the user's body, enabling the users to better perceive the haptic patterns. With this requirement in view, two vests (one of medium size and the other of large size) have been obtained by custom-tailoring, to achieve the best fitting for the bodies of the participants. The distribution of the actuators has been determined based on the discrimination distances obtained by previous experiments [8], and by ensuring that the haptic patterns would be reliable and easy to be perceived by the users. The following are the details of actuators used:

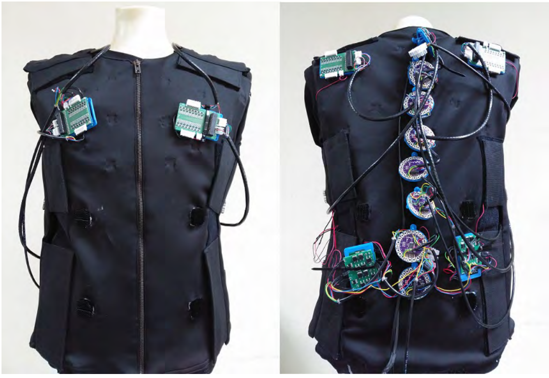

FIGURE 1. Haptic Vest seen from (left) the front and (right) from the rear. The hardware control units (microcontrollers, PCBs and power supply system) are strategically located at the back, so that they do not obstruct the user's movements.

- Vibration motors (model '304-116', Precision Microdrives, www.precisionmicrodrives.com): These motors have a frequency range of 0 to 350 Hz when powered between 0 and 5 volts. The motors are fitted in a 3D printed support that has been sewn on the vest at selected locations to avoid relative movements on the vest. Motors are distributed over the upper chest, upper back and shoulders with a distance of 55 mm between two motors (the distance is slightly greater than the resolution distance [8]). The distribution of motors follows the pattern of an equilateral triangle (see Figure 2). Thus, 54 motors are placed on the large size vest and 38 motors on the medium size vest.

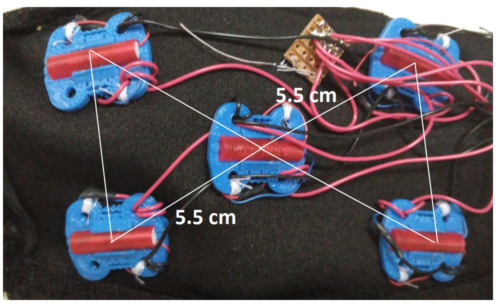

FIGURE 2. The distribution of motors follows the shape of an equilateral triangle: the motors shown here belong to a shoulder area.

- Peltier cells: (model 'TES1-07150', Everred Tronics, www.everredtronics.com): The model allows generation of heat and cold sensations due to Peltier physical effect, approximately between 0°C and 100°C. Literature shows that non-pain temperature ranges from 15°C to 45°C [38], and that the created thermal stimuli will be between within that range. The cell is fitted with a 3D printed support that is sewn on the vest at the points where these actuators are placed. One of the sides of the Peltier is in contact with the user, whereas the other side faces outside. A heat sink is placed on the free side of the Peltier to avoid overheating of the cell. The heat sink is fitted in the same place as the cell, forcing contact between the cell and the sink. The cells are located on the lower back and the abdomen in a rectangular pattern, maintaining a distance of 15 × 20 cm among elements (see Figure 3). Thus, 12 Peltier cells are placed on the vest, regardless of the vest size.

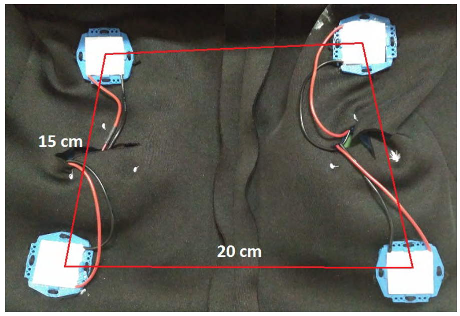

FIGURE 3. The distribution of Peltier cells follows a lineal pattern. These cells belong to an internal part of the back.

The actuators must be appropriately controlled to facilitate the programming of haptic patterns. The patterns have to be properly synchronized with the visual and audio stimuli of the VR system. The control comprises six microcontrollers (Arduino Lilypad, www.arduino.cc), whose outputs are sufficient enough to control all actuators. Moreover, the vibration motors and the Peltier cells require a Printed-Circuit Board (PCB) for the power stages to control 16 motors and 4 Peltier cells with the corresponding PCB. Thus, the control system on the whole consists of six Arduino boards, four PCBs for vibration motors and 3 PCBs for Peltier cells.

A. HAPTIC STIMULI

Interaction with the VE is made by using haptic patterns that reproduce virtual tactile interactions, which stimulate the user similarly as real contacts do, enabling the user to perceive the VE in a more realistic way. These patterns have been developed based on the parameters used in developing haptic stimuli and some characteristics of the haptic device, such as actuators distribution, minimum vibration threshold, etc. Two haptic interactions have been developed:

- Collision. This interaction is generated with vibration motors. In the VE, there are several colliders surround the user's Point of View (PoV) and they are placed at areas where the motors are attached: shoulders, chest, and back. When a collider comes in contact with a character or an object, it sends a signal to the vest controller, following which the motors are turned on and the collision pattern is reproduced.

  These vibrations simulate collisions with elements inside the VE. When a virtual collision is produced in a specific area, all motors associated with that area are turned on simultaneously within 250 milliseconds. The collision strength depends on the avatar velocity during the contact: if the contact is produced at low velocities (<1 m/s), the vibration frequency will be 150 Hz (smooth blow); if it is produced at high velocities (>1 m/s), the vibration frequency will be 300 Hz (strong blow).

- Temperature simulation. This interaction is reproduced with Peltier cells. The side of the Peltier cell, attached to the user's skin, reaches a temperature that considers the following three parameters:
  - *Stress:* The user feels stress sensation because he/she is moving around in an unfriendly environment (post-explosion scenario). The stress continuously increases the body temperature, because the user is working under a certain pressure during that time in the VE [39]. In a hostile environment, stress does not appear and disappear during a short time, and hence this increase must be continuous. The constant value corresponding to stress in equation (1) is 0.02 and is obtained experimentally, so that the temperature is increased slowly every second (t). The value is selected because smaller or greater values do not cause a realistic sensation on the users.
  - *Physical Activity:* If the user moves at high velocities, the temperature of the user increases due to physical activity. The constant value corresponding to this parameter is 0.01, which is also obtained experimentally. Just as the stress constant, smaller or greater values of physical activity cannot adjust to reality and hence produce strange temperature variations on the users. Therefore, variable velocity (v) is used for changing body temperature, depending on the physical activity [40].
  - *Closeness to the Fire:* Depending on the distance to the fire, the cells will reach a determined temperature: that is, if the avatar is 100 m from the fire, the cells will reach 34.9 °C. Thereon, as the avatar approaches the fire, the temperature increases linearly until a maximum of 45 °C (0 m from the fire). Therefore, equation (2) varies depending on the internal variable called 'HeatMag', which relates the virtual fire intensity to the avatar distance from the fire. When 'HeatMag' is 0, the avatar is 100 m from the fire and the temperature is 34.9 °C; when 'HeatMag' is 100, the avatar is 0 m from the fire and the temperature is 45 °C, which is the maximum value under the pain thermal threshold. The temperature increase is linear, so, the constant of 0.012 value is obtained by using the equation of a straight line, based on two points ('HeatMag' = 0 and 'HeatMag' = 100):

$$Temp_{s+pa} = (0.02 + 0.01 \cdot v) \cdot t \tag{1}$$

$$Temp_f = 0.112 \cdot HeatMag + 34.9 \tag{2}$$

Then, the final temperature generated by the cells would be the sum of these two quantities (3). The temperature, which is due to closeness to the fire is displayed only when the heat source is activated (HS = 1).

$$Temp = Temp_{s+pa} + HS \cdot Temp_f \tag{3}$$

It needs to be stressed here that the increase in temperature, due to stress or physical activity, is not reversible. Therefore, successive increments of temperature keep accumulating during simulation. However, if the user distances from the fire, the temperature diminishes, but only until the value attained due to stress and physical activity.

It should be pointed out that the response time of Peltier cells is adequate enough to perceive all the thermal stimuli properly. The standby temperature, when the cells on the vest come in contact with the user body, is around 30-32 °C, depending on the user. Moreover, to remain within the pain thermal threshold, the maximum reachable temperature is 45 °C. In such a case, the time required to increase the temperature from 30 to 45 °C is 8 seconds, whereas for intermediate temperatures, it is lesser. However, the perception of environmental heat has to be gradual and not sudden, so that the user can feel a continuous increase in temperature, until attaining the final objective.

IV. VIRTUAL ENVIRONMENT DEVELOPMENT

VE is used as a tool for evaluating the functionalities of the vest and its capabilities, using a serious game for first responders training. The evaluation is carried out by simulating virtual events through haptic stimuli (tactile and thermal interactions), based on which the users can evaluate how those interactions affect their experience inside the VE. Moreover, high quality computer graphics is the basic requirement for the game, as already mentioned in the previous section. Then, the VE has been developed using Unity, because it provides powerful tools to create high quality realistic computer graphics.

FIGURE 4. The Virtual Environment corresponding to the train station displayed in the experiment.

The users wear a Head-Mounted Display (HMD) [HTC Vive, www.vive.com] and a haptic vest, following the role of a first responder. The user moves inside a scenario, configured as a post-explosion train station, accesses to the area and evaluates the emergency situation, in such a way that he or she can interact with the whole virtual system. Figure 4 shows the VE developed.

Vest control is based on master-slave architecture, wherein a computer runs the master application and the vest controller acts as the slave. In such a situation, the communication always flows in a single direction towards the vest, via Bluetooth. The interface communicates with the vest controller which activates the actuators using the corresponding drivers. The power supply is taken from a wall plug or a power source.

The vest is wirelessly controlled, using Bluetooth 4.0 protocol, also known as BLE (Bluetooth Low Energy), to ensure operation compatibility with a wide range of devices. It is assumed that the MAC address of the Bluetooth module, connected to the controller, is known, and the master where the environment runs, is synchronized with that module before the VE starts. Figure 5 shows the complete communication scheme of the haptic vest.

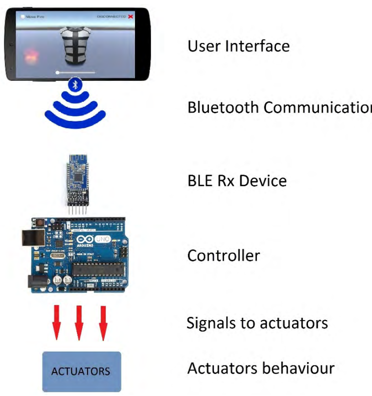

FIGURE 5. Vest communication and control scheme.

Once the connection is established, information messages will be generated and transmitted to the controller, depending on the user interactions with the VE. The messages so generated contain simple commands about the patterns to display over users. The controller receives these messages through the Bluetooth channel, which in turn triggers the corresponding signals to control the proper actuators.

The operation of the actuators depends on the interactions of the avatar with the VE. Two types of interactions (collision and heat) can be activated during the user interaction with the VE.

V. EXPERIMENTAL SYSTEM

The main objective of the experiments is to ascertain if the vest, using tactile and thermal actuators, can improve the performance of a serious game, in terms of enhancing realism or sense of presence inside the VE. Before programming the experiment, the participants have been classified into three groups depending on their experience with haptic and VR technology: HE, TE and NE groups. By doing so, it is possible to ascertain if experience causes, in a multimodal system, differences in the perception of the VE and if an additional device (the haptic vest) affects the multimodal environment performance.

A. EXPERIMENTAL PROCEDURE

To perform the experiment, the user has to first wear the HMD with headphones, and the haptic vest. The vest has already been configured to interact properly with the VE. Besides, the HMD has been calibrated to limit the space for the user's movement, while carrying out this experiment with the help of the HMD trackers. Figure 6 shows two participants during the experiment.

FIGURE 6. Two participants during the experiment.

Once the system has been initiated, the user interacts with the environment in two different phases:

- First phase. The virtual avatar is displayed in a central point of the train station and the users are asked to move around freely in the VE. In this manner, the user can perceive tactile interactions with the rest of the characters and the objects when the user's avatar makes contact with any of them. This phase takes around two minutes for the user to explore the scenario completely.
- Second phase. The fire simulation is activated, following which fire appears on one side of the train station. The user is requested to approach that area and when the user approaches the fire, the temperature of the vest increases gradually. Thus, the user will feel strong sensation of heat by being next to the fire inside the established limits. Finally, it is important to note that fire is not the only stimulus that is generating sensation of heat inside the VE, because body temperature also can increase due to internal parameters of the virtual avatar. This phase takes around 4-5 minutes.

B. PARTICIPANTS

Twenty-three healthy people aged between 23 and 53 years ($M = 33.43$; $SD = 7.34$), participated in the experiment. They have been divided into three groups, depending on their knowledge of haptics and VR devices. The division has been done after analyzing their answers to a questionnaire, among which some questions were framed to facilitate participants' division into groups.

C. EVALUATION QUESTIONNAIRE

Once the experiment has been performed, the participants are asked to answer a questionnaire. The objective of the questionnaire is two-fold: (i) Classifying the participants, based on their knowledge of haptics and VR; (ii) analyzing how haptic devices affect the participants' sense of presence inside the VE. It is important to note that presence is a subjective parameter, and that is why the results depend on the participant opinion and, thus, their answers depend on their level of expertise.

As the experiments are performed in two phases, the participants are asked to answer the questionnaire only after finishing both phases so that they can evaluate the experiments jointly, by comparing the perceived sensations during the tests.

TABLE 1. Evaluation questionnaire.

Block	Questions
Classification of participants	1. Have you ever used any haptic device? 2. Have you ever used any VR device? 3. Have you ever worked with haptics and VR devices?
Haptic Devices Contribution to Realism or Presence	4. How do you evaluate the realism level of your VR experience? 5. Do you think a haptic device could be useful to improve presence and/or realism in VEs? 6. What parameter? Presence or realism?
Evaluation of Tactile Stimuli	7. Have you perceived any tactile stimulus? 8. Could you associate those stimuli with events that happened inside the VE? 9. Select what event you could associate with the stimulus? 10. Value the realism level of the sensations perceived
Evaluation of Thermal Stimuli	11. Have you perceived any thermal stimulus? 12. Could you associate those stimuli with events that happened inside the VE? 13. What event do you associate with the stimulus? 14. Assign score to the realism level of the sensations you perceived.

The questionnaire has fourteen questions, divided into four blocks, as shown in Table 1. The first block includes three questions aimed at classifying the participants into three groups (HE, NE and TE).

The second block establishes user's expectations on the abilities of the haptic device in improving realism or sense of presence in the VE. The first question is answered, based on the perceived sensations from the VE, without considering the influence of haptic stimuli. The two subsequent questions determine if the participants believe that their sensations can be improved by using the haptic vest.

The third and fourth blocks correspond to the evaluation of tactile and thermal stimuli. The two blocks contain similar questions, each focused on the corresponding haptic interaction. The aim is to ascertain if the participants have perceived any kind of stimuli and if the answer is in the affirmative, then whether they can relate those stimuli to the events that happened in the VE.

These questions evaluate the perception of different stimuli without considering the real values generated over the participant (temperature or frequency values); however, those values are always within the thresholds cited in literature, and are hence perceivable by humans (vibration thresholds, pain thermal threshold, etc.) [8], [39]. This kind of evaluation is used, because perception is subjective and different users perceive stimuli in different ways; for instance, each user has different pain thermal thresholds (regarding Peltier cells and thermal stimuli) and perceives vibration frequency and intensity in a different way than the rest of the users.

In some questions, the participant is asked to select one or more options from a list of events that possibly happened in the VE. The list is composed of events truly displayed on the vest (e.g., closeness to fire, stress, etc.), although not all events are displayed (such as snow or air conditioning). Thus, the answers to the questionnaire demonstrate if the participants could identify the events that were truly displayed. The last question of this block relates to the realism of haptic stimuli.

TABLE 2. Scale for measuring presence inside VEs.

Score	Perception
0	Not realistic, unnatural
1	Poorly credible
2	Artificial, non-immersive
3	Artificial but immersive
4	Realistic, non-immersive
5	Realistic and immersive
6	Real, some details are not immersive
7	Totally Real

All questions about realism are evaluated using a numeric scale, related to different realism or artificiality levels of visual or haptic stimuli (see Table 2). The details of each option are given below:

- Options 0-1: The environment or stimuli are not realistic.
- Options 2-3: Poor environment or stimulation, i.e., although they could be similar to real, several factors render the system perceive them as poorly realistic. The two options are differentiated depending on the level of presence reached in spite of the artificiality.
- Options 4-5: Realistic environment or stimulation, i.e., there are many similarities to reality. Once again, the two options are differentiated according to the level of presence, because it is possible to perceive the environment realistically, though not in an immersive way.
- Option 6: A scenario or stimulation with high realism is very similar to a real environment or stimulus. Some details might reveal that it is VE, but those details do not affect presence.
- Option 7: A scenario/stimulation that is totally realistic. Some differences may or may not be there, between reality and the VE.

VI. EXPERIMENTAL RESULTS

A. PARTICIPANTS CLASSIFICATION

The answers to the first three questions are used to group the participants into three categories, as detailed below, based on their experience with haptic devices and VE systems.

- Haptic Experts (HE): Nine participants had experience working with haptic or VR systems. They are aged between 24 and 53 years (M = 35.89; SD = 9.64).
- Technology Experts (TE): Six participants have tried some haptic or VR device, but not participated in any research activity. These participants are aged between 26 and 31 years (M = 26.5; SD = 2.95).
- Non-Experts (NE): Of the remaining eight participants, four have no experience either with haptics devices or VR systems, whereas the other four have previously tried VR devices. These participants are all aged between 34 and 40 years (M = 37.13; SD = 1.75).

B. VIRTUAL ENVIRONMENT REALISM AND USEFULNESS OF HAPTICS

The next step is to evaluate the VE without considering the haptic from the vest. By ignoring the haptic stimuli at this stage, the participants will have a starting point to evaluate the influence of haptic stimuli on the presence or realism. In other words, all the subsequent results will be studied with that orientation. The results are shown in Table 3.

TABLE 3. Virtual environment evaluation.

Group	Realism Score
All participants	3.62 ± 1.73
HE	2.44 ± 1.88
TE	3.67 ± 1.03
NE	4.75 ± 1.16

Moreover, the questions of this block are aimed at finding out whether the participants believe that the haptic vest is useful for VE, more specifically, for improving the presence or realism. All participants believe that the haptic vest improves the presence and realism, although some believe that realism is not improved with this kind of device. The answers to this block of questions are summarized in Table 4. These answers are used for analyzing the subsequent blocks.

TABLE 4. Influence of the haptic device in VE properties.

Group	Usefulness	Presence	Realism
All participants (23)	100 %	100 %	87 %
HE (9)	100 %	100 %	67 %
TE (6)	100 %	100 %	100 %
NE (8)	100 %	100 %	100 %

C. EVALUATION OF TACTILE AND THERMAL STIMULI

The next blocks of questions address the influence of haptic stimuli during the experiment. First, the participants are asked if they have perceived any stimuli (tactile or thermal) during the experiment and if so, whether they can associate them with the events inside the VE. Next, the participants are asked to identify the specific associated events among a list of options offered in the questionnaire. Finally, the participants are asked to evaluate the realism level of the identified stimuli, according to the scale previously defined (Table 2). This evaluation has to be done separately for tactile and thermal stimuli, as shown in Tables 5 and 6, respectively.

TABLE 5. Tactile stimulation evaluation.

Group	Perception	Association to Events	Kind of Events	Realism Score
All (23)	100 %	78 %	---	3.89 ± 1.18
HE (9)	100 %	56 %	Collisions, wind	3.5 ± 1.07
TE (6)	100 %	83 %	Collisions	3.8 ± 1.1
NE (8)	100 %	100 %	Collisions	4.38 ± 1.3

TABLE 6. Thermal stimulation evaluation.

Group	Perception	Association to Events	Kind of Events	Realism Score
All(23)	91 %	78 %	---	4.31 ± 1.65
HE (9)	78 %	44 %	Closeness to fire, temperature	3 ± 1.32
TE (6)	100 %	100 %	Closeness to fire	4.17 ± 1.33
NE (8)	100 %	100 %	Closeness to fire, stress, fatigue	5.75 ± 0.89

Participants can provide comments about the VR system, as a whole. According to their comments, the system has to improve the realism of tactile stimuli. The other main drawback is desynchronization between the events in the VE and the vibrotactile responses. The need to explore the possibility of including more tactile sensations has been stressed by some participants. Apart from these, some participants reported unequal heating in different parts of the vest. On the positive side, most of the participants have reported improvement in the system, in terms of presence and realism, by using the haptic vest.

VII. DISCUSSION

The valuation of the VE (only audio and video) realism is 3.62 over 7 points, with high standard deviation in some groups (see Table 8 & Figure 7). These high values require evaluation because they serve as a reference to evaluate the influence of the haptic vest. The differences among the groups are analyzed using ANOVA [41] test with the three group samples. The test gave a p-value of 0’014, which indicates significant difference between the groups. However, this test cannot find out the cause for those differences; so, three Student t-tests are performed between pairs of samples. The results of t-tests

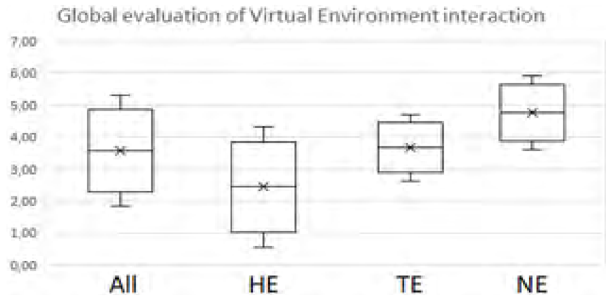

FIGURE 7. Evaluation of the Virtual Environment realism, on a scale of 0 to 7, according to Table 2. 'All' denotes the results of all users: HE (Haptic Expert), TE (Technology Expert) and NE (Non-Expert).

show a significant difference among TE-NE (p-value = 0'045) and HE-NE (p-value = 0'004) groups, but no significant difference among HE-TE groups, whose p-value is greater than 0'05 (limit value for considering significant differences). Thus, the NE group perceives greater realism and presence, because they have never tried a system (including haptics), similar to the one they now used, which increases the number of sensations provided by the VE, whereas, the HE and TE groups need more realistic experience to perceive meaningful improvements. These results are showed in Table 7.

TABLE 7. Statistical analysis VE evaluation.

Groups	Test	p-value
All	ANOVA	0.014
HE-TE	Student t-test	> 0.05
TE-NE	Student t-test	0.045
HE-NE	Student t-test	0.004

Regarding evaluation of tactile patterns, only five participants did not associate the stimuli with the events inside the VE. This could be because of desynchronization between event-haptic patterns or lack of stimuli realism, with respect to real contacts. However, most of the participants could relate the events and the haptic responses. Once again, these five participants from HE group do not relate the events appropriately and those differences could be due to those users need a perfect stimulation to identify and value the haptic patterns positively. Likewise, two participants did not perceive thermal stimuli and three more participants could not associate the stimuli with virtual events. All those participants also belong to HE group. Just as in the previous case, the participants possibly needed a greater level of realism to appreciate the events and relate them properly with the VE (e.g., improving heat control or tightening the vest to the body).

In most cases, the participants could properly relate the events with the haptic patterns displayed. For instance, tactile stimuli are always associated with objects' or characters' contacts, and thermal stimuli with closeness to fire or ambient temperature. In some cases, the NE group associated the thermal stimuli with stress or fatigue, indicating that they have greater propensity to perceive non-physical events because of their lower expertise and greater impressionability.

Valuations of both types of stimuli show that thermal stimuli are better evaluated than tactile stimuli, probably because thermal stimuli are generally more similar to real sensations; even so, there is room for increasing the realism, according to the perceptions of HE and TE groups. Regarding tactile stimuli, the valuations are similar between groups, indicating that realism levels can be substantially improved since all evaluations are around 3.5 over 7 points. For comparison, the results are shown in Figure 8.

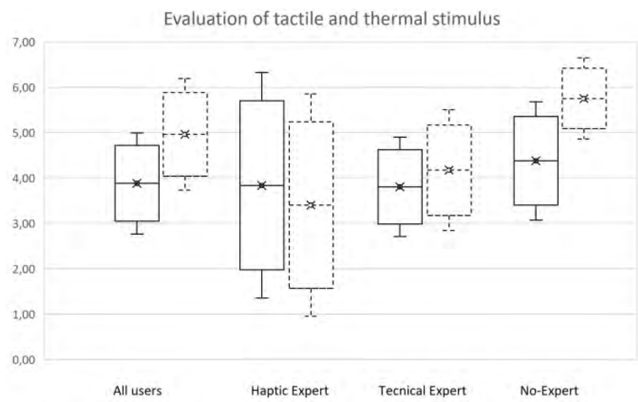

FIGURE 8. Evaluation of tactile (solid line) and thermal (dash line) stimulus according to the realism scale in Table 2.

Two ANOVA tests are performed to evaluate the tactile and thermal stimuli, only in terms of the differences in thermal stimuli (p-value $= 5 \cdot 10^{-4}$) between the groups. Likewise, six Student t-tests are performed comparing the groups in pairs to confirm the hypothesis of tactile stimuli (all p-values are greater than 0'05). The t-test results for thermal stimuli show that HE and TE groups perceive the stimuli in similar ways, whereas the NE group perceives in a way significantly different from that of HE group (p-value $= 8'33 \cdot 10^{-5}$) and TE group (p-value = 0'018). This is attributable to the lack of experience of the NE group participants, who are disposed to perceive the new kind of stimuli more satisfactorily with considerable similarity to the real interaction. All the results are shown in Table 8.

TABLE 8. Statistical analysis for tactile and thermal stimuli.

Groups	Test	p-value (Tactile)	p-value(Thermal)
All	ANOVA	> 0.05	$5 \cdot 10^{-4}$
HE-TE	Student t-test	> 0.05	> 0.05
TE-NE	Student t-test	> 0.05	0.018
HE-NE	Student t-test	> 0.05	$8.33 \cdot 10^{-5}$

In conclusion, it can be stated that the valuation of all the groups, in terms of their haptic interactions, is greater than 3.5 points, although there is admittedly good scope for improvement. Nonetheless, it must be stressed that the vest

TABLE 9. Main features of professional and general users.

Features	General Users	Professional Users
Event Synchronization	Medium	High
Vest Fitting	Medium	Medium
Tactile Stimuli	High	High
Thermal Stimuli	Medium	High

helped the VE and HE participants in improving presence and realism, although problems like lack of synchronization and heat control are yet to be satisfactorily addressed. There are significant differences between experts and novices, indicating that less realistic systems would better serve the purpose of general public, because their expectations are fewer than those of the experts. Once these systems become accessible to general public, then greater realism levels will be needed to achieve the same evaluations.

Finally, the results show that the level of expertise of the end-users should be taken into account in designing the haptic vest, because the expectations of haptic experts (professionals) and non-experts (general users). The results are classified into three levels, low, medium and high, depending on the groups expectations, in terms of four features. The levels are selected, depending on whether the group needs a basic, medium or a specialized functionality of those features.

As regards synchronization between haptic events and the VE, the professionals need better synchronization than the general users to improve realism and presence. This applies even to thermal stimuli, because general users are not used to experiment this kind of feedback. In the case of tactile stimuli, however, both groups need high quality synchronization to perceive the sensations as realistically as possible. However, vest-fitting is not a key feature since both groups need only a medium level functionlaity to perceive the events properly. Table 9 summarizes the main features of the two kinds of users.

VIII. CONCLUSION

This study evaluates the influence of haptic vest inside a VR system by performing some experiments. During the experiments, the participants have moved around the VE, perceiving multimodal stimuli: video, audio and haptics. After the experiments, the users have offered their answers to a questionnaire, which helped in evaluating the VE and their interactions with the haptic vest. Their answers show that most of the users agree on the usefulness of the haptic vest for improving the performance of the VE, notwithstanding the divergence of opinion among the experts. This inference is reinforced by subsequent results, which show that professional users value the tactile and thermal stimuli less positively than the thermal stimuli, which are always better valued because of their similarities to real sensations. Over all, it should be pointed out that, in most cases, the events that happened in the VE could be properly identified with the help of the stimuli generated by the vest. Therefore, in conclusion, the participants' answers to the questionnaire show that the haptic vest improves realism and the sense of presence in the VE.

There are some differences among the groups, obtaining two kinds of users: professional and general. Professional users have experience in haptics, VR or experience with serious games (learning, training, etc.); whereas, general users have little to no experience at all. The differences in perception between the participants are related to the differences in their expectations with VEs or haptic interactions. The professionals need high quality thermal stimuli than general users, because the latter have had any no previous experience with this kind of stimulation and hence they can accept only more basic functionalities. On the other hand, in the case of tactile stimuli, stimulation could be attained by many users, implying thereby that the professional and general users require, more or less, the same level of specialization. In the same way, the professional users need a more specialized synchronization than general users between VE events and multimodal stimulation (audio, video and haptics) to achieve the same satisfaction level.

The professionals are more interested in serious games and the general users in VR systems for entertainment. Therefore, a greater effort is needed in order to develop quality stimuli and proper synchronization for serious games than that needed for the applications of VE entertainment.

REFERENCES

[1] M. Slater and M. V. Sanchez-Vives, "Enhancing our lives with immersive virtual reality," *Frontiers Robot. AI*, vol. 3, p. 74, Dec. 2016.
[2] N. Magnenat-Thalmann and U. Bonanni, "Haptics in virtual reality and multimedia," *IEEE MultimediaMag.*, vol. 13, no. 3, pp. 6–11, Jul. 2006.
[3] R. J. Stone, "Haptic feedback: A brief history from telepresence to virtual reality," in *Haptic Human-Computer Interaction* (Lecture Notes in Computer Science), vol. 58. Berlin, Germany: Springer, 2001, pp. 1–16.
[4] B. Whitsell and P. Artemiadis, "Physical human–robot interaction (pHRI) in 6 DOF with asymmetric cooperation," *IEEE Access*, vol. 5, pp. 10834–10845, 2017.
[5] G. Korres and M. Eid, "Haptogram: Ultrasonic point-cloud tactile stimulation," *IEEE Access*, vol. 4, pp. 7758–7769, 2016.
[6] D.-H. Kim and S.-Y. Kim, "Immersive game with vibrotactile and thermal feedback," in *Proc. 5th IEEE Int. Conf. Comput. Sci. Conv. Inf. Technol. (ICCIT)*, Nov./Dec. 2010, pp. 903–906.
[7] O. Bau and I. Poupyrev, "REVEL: Tactile feedback technology for augmented reality," *ACM Trans. Graph.*, vol. 31, no. 4, p. 89, 2012.
[8] G. García-Valle, M. Ferre, J. Breñosa, R. Aracil, J. M. Sebastian, and C. Giachritsis, "Design and development of a multimodal vest for virtual immersion and guidance," in *Proc. Int. Conf. Human Haptic Sens. Touch Enabled Comput. Appl.*, 2016, pp. 251–262.
[9] W. Ribbens, S. Malliet, R. Van Eck, and D. Larkin, "Perceived realism in shooting games," *Comput. Human Behavior*, vol. 64, pp. 308–318, Nov. 2016.
[10] M. V. Sanchez-Vives and M. Slater, "From presence to consciousness through virtual reality," *Nature Rev. Neurosci.*, vol. 6, no. 4, pp. 332–339, Apr. 2005.
[11] M. Slater, P. Khanna, J. Mortensen, and I. Yu, "Visual realism enhances realistic response in an immersive virtual environment," *IEEE Comput. Graph. Appl.*, vol. 29, no. 3, pp. 76–84, May/Jun. 2009.
[12] M. Minsky, "Telepresence," Omni Mag., pp. 45–51, 1980.
[13] M. J. Schuemie, P. van der Straaten, M. Krijn, and C. A. van der Mast, "Research on presence in virtual reality: A survey," *CyberPsychol. Behavior*, vol. 4, no. 2, pp. 183–201, 2001.
[14] M. E. Altinsoy, "The quality of auditory-tactile virtual environments," *J. Audio Eng. Soc.*, vol. 60, nos. 1–2, pp. 38–46, 2012.

[15] A. M. Kappers, ''Human perception of shape from touch,'' *Philos. Trans. Roy. Soc. London B, Biol. Sci.*, vol. 366, no. 1581, pp. 3106–3114, 2011.
[16] J. Lee, Y. Kim, and G. J. Kim, ''Effects of visual feedback on out-of-body illusory tactile sensation when interacting with augmented virtual objects,'' *IEEE Trans. Human-Mach. Syst.*, vol. 47, no. 1, pp. 101–112, Feb. 2017.
[17] J. Moll, Y. Huang, and E.-L. Sallnäs, ''Audio makes a difference in haptic collaborative virtual environments,'' *Interact. Comput.*, vol. 22, no. 6, pp. 544–555, 2010.
[18] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, ''Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review,'' *Psychonomic Bull. Rev.*, vol. 20, no. 1, pp. 21–53, 2013.
[19] B. Witmer and M. Singer, ''Measuring presence in virtual environments: A presence questionnaire,'' *Presence*, vol. 7, no. 3, pp. 225–240, Jun. 1998.
[20] C. Lee, G. A. Rincon, G. Meyer, T. Höllerer, and D. A. Bowman, ''The effects of visual realism on search tasks in mixed reality simulation,'' *IEEE Trans. Vis. Comput. Graphics*, vol. 19, no. 4, pp. 547–556, Apr. 2013.
[21] E. Giannopoulos, Z. Wang, A. Peer, M. Buss, and M. Slater, ''Comparison of people's responses to real and virtual handshakes within a virtual environment,'' *Brain Res. Bull.*, vol. 85, no. 5, pp. 276–282, 2011.
[22] L. Meli, C. Pacchierotti, and D. Prattichizzo, ''Sensory subtraction in robot-assisted surgery: Fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction,'' *IEEE Trans. Biomed. Eng.*, vol. 61, no. 4, pp. 1318–1327, Apr. 2014.
[23] P. Ramsamy, A. Haffegee, R. Jamieson, and V. Alexandrov, ''Using haptics to improve immersion in virtual environments,'' in *Proc. Comput. Sci. (ICCS)*, Reading, U.K., 2006, pp. 603–609.
[24] M. A. Otaduy, A. Okamura, and S. Subramanian, ''Haptic technologies for direct touch in virtual reality,'' in *Proc. ACM SIGGRAPH Courses*, 2016, p. 13.
[25] L. A. Jones, M. Nakamura, and B. Lockyer, ''Development of a tactile vest,'' in *Proc. 12th Int. Symp. Haptic Int. Virtual Environ. Teleoper. Syst. (HAPTICS)*, 2004, pp. 82–89.
[26] J. B. F. Van Erp, H. A. H. C. Van Veen, C. Jansen, and T. Dobbins, ''Waypoint navigation with a vibrotactile waist belt,'' *ACM Trans. Appl. Perception*, vol. 2, no. 2, pp. 106–117, 2005.
[27] R. W. Lindeman, J. L. Sibert, C. E. Lathan, and J. M. Vice, ''The design and deployment of a wearable vibrotactile feedback system,'' in *Proc. IEEE Int. Symp. Wearable Comput.*, vol. 1. Oct./Nov. 2004, pp. 56–59.
[28] C. McGregor, B. Bonnis, B. Stanfield, and M. Stanfield, ''Design of the ARAIG haptic garment for enhanced resilience assessment and development in tactical training serious games,'' in *Proc. IEEE 6th Int. Conf. Consum. Electron.*, Berlin, Germany, Sep. 2016, pp. 214–217.
[29] E. van der Meulen, M. A. Cidota, S. G. Lukosch, P. J. M. Bank, A. J. C. van der Helm, and V. T. Visch, ''A haptic serious augmented reality game for motor assessment of Parkinson's disease patients,'' in *Proc. IEEE Int. Symp Mixed Augmented Reality*, Sep. 2016, pp. 102–104.
[30] S. C. Gobron *et al.*, ''Serious games for rehabilitation using head-mounted display and haptic devices,'' in *Proc. Int. Conf. Augmented Virtual Reality*, 2015, pp. 199–219.
[31] X. Hou, O. Sourina, and S. Klimenko, ''Haptic-based serious games,'' in *Proc. Int. Conf. Cyberworlds*, 2014, pp. 36–49.
[32] A. Chan, K. MacLean, and J. McGrenere, ''Designing haptic icons to support collaborative turn-taking,'' *Int. J. Human-Comput. Stud.*, vol. 66, no. 5, pp. 333–355, 2008.
[33] M. Azadi and L. A. Jones, ''Evaluating vibrotactile dimensions for the design of tactons,'' *IEEE Trans. Haptics*, vol. 7, no. 1, pp. 14–23, Mar. 2014.
[34] A. Israr, S. Zhao, K. Schwalje, R. Klatzky, and J. Lehman, ''Feel effects: Enriching storytelling with haptic feedback,'' *ACM Trans. Appl. Perception*, vol. 11, no. 3, p. 11, 2014.
[35] S. Zhao, J. Lehman, A. Israr, and R. Klatzky, ''Using haptic inputs to enrich story listening for young children,'' in *Proc. 14th Int. Conf Interaction Design Children*, 2015, pp. 239–242.
[36] D. L. Riddle and R. J. Chapman, ''Tactile language design,'' in *Proc. Human Factors Ergonom. Soc. Annu. Meeting*, 2012, vol. 56. no. 1, pp. 478–482.
[37] R. W. Cholewiak and A. A. Collins, ''The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mode,'' *Attention, Perception, Psychophys.*, vol. 62, no. 6, pp. 1220–1235, 2000.
[38] L. A. Jones and H. N. Ho, ''Warm or cool, large or small? The challenge of thermal displays,'' *IEEE Trans. Haptics*, vol. 1, no. 1, pp. 53–70, Jan. 2008.
[39] T. Oka, ''Psychogenic fever: How psychological stress affects body temperature in the clinical population,'' *Temperature*, vol. 2, no. 3, pp. 368–378, 2015.
[40] M. Gleeson, ''Temperature regulation during exercise,'' *Int. J. Sports Med.*, vol. 19, no. S2, pp. S96–S99, 1998.
[41] A. Cuevas, M. Febrero, and R. Fraiman, ''An anova test for functional data,'' *Comput. Statist. Data Anal.*, vol. 47, no. 1, pp. 111–122, 2004.

GONZALO GARCÍA-VALLE received the B.S. degree in electronics and automation engineering and the M.S. degree in automation and robotics from the Universidad Politécnica de Madrid, Madrid, Spain, in 2014 and 2016, respectively, where he is currently pursuing the Ph.D. degree in automation and robotics.

Since 2015, he has been a Researcher in automation and robotics with the Centre for Automation and Robotics, UPM-CSIC. His research interests include haptic devices and wearables applied to the human body, thermal and vibrotactile displays, development of innovative haptic actuators, perception, and psychophysics and, presence and realism of virtual environments.

MANUEL FERRE (A'01–M'04) received the Laurea degree in control engineering and electronics and the Ph.D. degree in automation and robotics from the Universidad Politécnica de Madrid (UPM), in 1992 and 1997, respectively. He held a post-doctoral position at the Human–Machine System Laboratory, Massachusetts Institute of Technology. He is currently a Professor Titular with UPM and the Director of the Centre for Automation and Robotics, UPM-CSIC.

He has participated and coordinated several research projects in robotics and automatic control at national and international programs. He has four patents of haptic devices and stereoscopic video cameras. He is an author of over 150 publications. His research interest is focused on automatic control, advanced telerobotics, and haptics. He is an Editor of the *Springer Series on Touch and Haptics System*.

Dr. Ferre has participated in the organization of several IROS and EuroHaptics conferences, hosting the EuroHaptics 2008 Conference. He is a member of the EuroHaptics Society, euRobotics, and CEA. He has served as the chair of serveral committees. He currently serves as a Treasurer of EuroHaptics Society and the Chair of the euRobotics Technical Committee on Telerobotics and Teleoperation.

JOSE BREÑOSA received the B.S. degree in industrial engineering, and the M.S. and Ph.D. degrees in automation and robotics from the Universidad Politécnica de Madrid, Madrid, Spain, in 2009, 2011, and 2016, respectively.

Since 2011, he has been a Researcher in automation and robotics with the Centre for Automation and Robotics, UPM-CSIC. His research interests include teleoperation and bilateral control systems, design and development of haptic interfaces for teleoperation, remote handling of fusion nuclear applications, haptic devices and force-feedback mechatronic hardware applied to the human body.

DAVID VARGAS received the B.S. degree in telematics from Universidad Rey Juan Carlos, Madrid, Spain, in 2015, and the M.S. degree in automation and robotics from the Universidad Politécnica de Madrid, Madrid, Spain, in 2017.

Since 2017, he has been a Researcher in automation and robotics with the Centre for Automation and Robotics, UPM-CSIC. His research interests include development of augmented and virtual reality applications, haptic devices oriented to virtual reality applications and general robotics.