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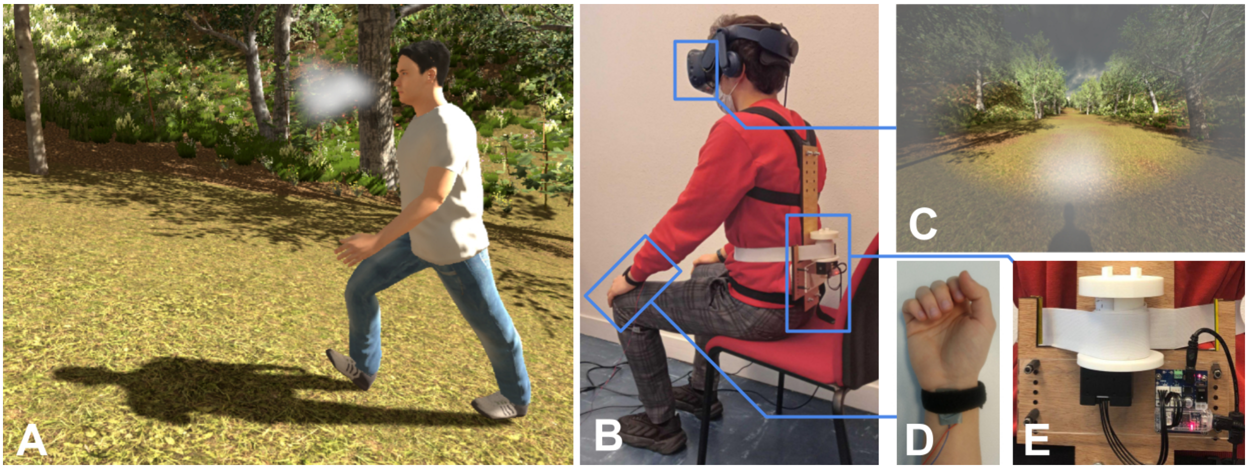

Fig. 1. We propose a novel approach to increase the connection with a self-avatar in virtual reality (A), by displaying its physiological state and physical exertion. It is based on a multi-sensory setup (B) involving visual, auditory and haptic displays. It includes visual effects such as a periphery overlay (C) simulating heart beating ; or haptic stimulation delivered with a piezoelectric actuator (D) and a novel compression belt (E) which exerts pressure on the abdomen to simulate a virtual breathing.

Abstract— In this paper we explore the multi-sensory display of self-avatars' physiological state in Virtual Reality (VR), as a means to enhance the connection between the users and their avatar. Our approach consists in designing and combining a coherent set of visual, auditory and haptic cues to represent the avatar's cardiac and respiratory activity. These sensory cues are modulated depending on the avatar's simulated physical exertion. We notably introduce a novel haptic technique to represent respiratory activity using a compression belt simulating abdominal movements that occur during a breathing cycle. A series of experiments was conducted to evaluate the influence of our multi-sensory rendering techniques on various aspects of the VR user experience, including the sense of virtual embodiment and the sensation of effort during a walking simulation. A first study (N=30) that focused on displaying cardiac activity showed that combining sensory modalities significantly enhances the sensation of effort. A second study (N=20) that focused on respiratory activity showed that combining sensory modalities significantly enhances the sensation of effort as well as two sub-components of the sense of embodiment. Interestingly, the user's actual breathing tended to synchronize with the simulated breathing, especially with the multi-sensory and haptic displays. A third study (N=18) that focused on the combination of cardiac and respiratory activity showed that combining both rendering techniques significantly enhances the sensation of effort. Taken together, our results promote the use of our novel breathing display technique and multi-sensory rendering of physiological parameters in VR applications where effort sensations are prominent, such as for rehabilitation, sport training, or exergames.

Index Terms—Avatar, multi-sensory display, haptic, physiological computing, effort sensation, embodiment, cardiac, respiration

1 Introduction

Self-avatars are more and more used in immersive Virtual Reality (VR) simulations. In the last decade, researchers have explored various means of enhancing the user experience when being virtually embodied in a self-avatar [19]. This can become challenging for VR applications in which the user has little control over their avatar, such as when using controllers with few degrees of freedom or when viewing simulated body animations. To improve such experience, different approaches of sensory stimulation have been explored. They can be categorized according to the theory of mind proposed by Leslie [34,40], which identifies three main sources of information that influence human behavior: Exteroceptive, Proprioceptive, and Interoceptive. Exteroceptive cues are sensory cues related to the perception of the body from the outside. Examples of simulated exteroceptive cues include vibratory haptic displays used to simulate virtual contact [3,36,50]. Proprioceptive cues relate to the perception of the position and movements of our body parts. For instance, walking-in-place techniques perform better in terms of presence than hand-pointing techniques [47] because proprioceptive cues have a better correspondence with the simulation. Interoceptive cues relate to the perception of our physiological state, that is the state of our body or bodily functions which can be described by parameters like heart rate, breathing rate, body temperature, etc. These cues remain largely underexploited by the VR research community up to now.

In this paper, we aim to enhance user experience in embodied VR by displaying fake interoceptive cues corresponding to the avatar's

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simulated activity in the virtual environment. Our approach consists in a systematic exploration of multi-sensory feedback (gathering visual, auditory, and haptic cues) for displaying the avatar's cardiac and respiratory activity to the user, extending previous work that focused only on cardiac activity [10]. We notably introduce a novel multi-sensory rendering technique for respiratory activity in VR by means of a haptic "compression belt" simulating abdominal movements that occur when breathing, where past work only comprised one example of such a technique that was adapted to scuba-diving simulations only [27]. Then, three user studies enable us to characterize the influence of our multi-sensory displays on users' sensation of effort, sense of embodiment, and sensation of walking during a VR locomotion simulation and contribute to better understanding the effect of displaying fake interoceptive cues on these aspects of user experience. The studies show a benefit of using our techniques on effort sensation and a moderate impact of displaying fake respiratory activity on embodiment.

In a nutshell, our main contributions can be summarized as follows:

- A multi-sensory approach simulating and displaying both the self-avatar's cardiac and respiratory activity.
- A novel technique to render respiratory activity in VR, including a dedicated haptic interface (compression belt), as well as consistent visual and auditory cues.
- A series of three experiments that assess the potential of our approach on several aspects of the user experience (effort sensation, sense of embodiment, walking sensation).

2 Related work

In this section, we discuss past work related to the display of physiological parameters linked to cardiac and respiratory activity in virtual environments. The section is split in two parts. The first one discusses the rendering techniques used in the past from a technical point of view. The second one focuses on past work assessing the influence of such displays on VR user experience.

2.1 Cardiac and respiratory representations in VR

In the past, researchers have designed physiological parameter displays that used one sensory modality only (vision, audition or haptics). Visual-only representations have been proposed for cardiac activity [4,9,21,49]. These representations range from classical 2D displays like a beating heart shape [21], a colored flash on peripheral vision [21], moving objects in the Virtual Environment (VE) [21], an aura around the avatar [4], numerical display and virtual bike speed [9], or color flash on the skin in AR [49]. Visual-only representations have also been suggested for respiratory activity [1,2,6,14,44,51,54]. For instance, it has been represented by avatar movements [14,54], an aura around the avatar [1,2,29], color changes in the VE [6,44], or a moving cloud [51]. Auditory-only rendering techniques have also been investigated. Cardiac activity has been represented with heartbeat sounds [22,25], and respiratory activity with breathing sounds [11]. Haptic-only representations have been investigated as well. For instance, vibratory stimulation has been used to display cardiac activity to users in VR, through the VR controllers [17], or using a smartwatch in a desktop game [42]. Outside VR, Ban et al. proposed a system that consists in placing an inflating and deflating cushion on the stomach [5] to slow down breathing and enhance relaxation. Overall, examples of uni-sensory display of cardiac activity have been reported for all three modalities, while no haptic-only display has been reported for respiratory activity.

Researchers have proposed representations of physiological parameters in VR that mix sensory modalities. Cardiac activity has been presented through audio-haptic displays [16,52] with heartbeat sounds and vibrations in controllers [16] or at footrest [52], and audio-visual displays [11,18,24,45], with visual and auditory changes in the VE [45], or heartbeat sounds combined with either a tunnel vision effect [11,24] or a beating heart shape [18]. In the past, only one example was reported of using all three sensory modalities to display heart rate in VR [10]. In the study, the user's cardiac activity was displayed with a beating heart shape, heartbeat sounds and vibrations in the VR controllers in order to induce an emotional response. Since the displayed heart rate was the user's, the display did not involve the avatar's activity. Another study compared the display of cardiac activity through pressure stimulation on the wrist, auditory and visual stimulation [12] but it was outside VR.

Respiratory activity has also been represented using multi-sensory displays. Audio-visual stimulation has been investigated, either with breathing sounds and avatar movement [38], or visual and auditory changes in the VE [45]. An example of audio-visuo-haptic display of respiratory activity has been designed in the past for a scuba diving simulator [27]. Respiratory activity was measured on the user and displayed with bubbles in the VE, and mapped to an up and down motion of an inflatable cushion placed under the user. This last work is the only example of a respiratory activity display using all three sensory modalities. However, the display can hardly be applied to other types of simulations and did not concern the representation of the avatar's activity in the VE.

Visual and auditory representations have then been investigated to render both cardiac and respiratory activities in VR. Haptic representations have also been proposed to represent cardiac activity. However, apart from the two examples given, which either cannot be applied to other types of simulations than scuba diving [27] or are not wearable [5], no haptic representation for breathing in VR has been designed in the past. Little work has focused on combining visual, auditory and haptic modalities to represent either cardiac activity or respiratory activity. Beyond combining sensory modalities, little work has investigated the combination of the physiological parameters themselves. The only examples reported are a biofeedback application [45] that used metaphorical display of cardiac and respiratory activity in augmented reality to induce relaxation, and a VE designed to induce anxiety by displaying heartbeats and breathing sounds [11]. These two examples did not assess the impact of combining the parameters compared to using only one of them.

2.2 Influence of physiological display on user experience

Various effects of displaying physiological parameters to users in VR have been identified, including an effect on users' actual physiology. When displaying a generated breathing through the avatar in first person perspective [14] and when sharing breathing between collaborators in VR [54], user breathing tended to synchronize with the displayed one. More generally and outside VR, rhythmic cues like placing an inflating and deflating cushion on the stomach [5], or a light and sound of oscillating intensity [20] can induce a synchronization of breathing activity with the displayed rhythm. The effect of displaying a modified or generated heart rate on users' actual heart rate are less obvious. A continuous rise of 20 beats per minute (bpm) starting from accurate heart rate was reported to increase actual heart rate by about 2 bpm [21]. Presenting a fast heart rate to users in a horrific virtual environment (VE) was also reported to have an impact on actual heart rate [52]. Outside VR, it was reported that a 120 bpm pressure stimulation on the wrist induced a rise in heart rate while equivalent auditory and visual stimulation did not [12]. In the same study, a 60 bpm pressure stimulation helped reduce heart rate while drawing. Overall, displaying a modified or generated heart rate has been reported to induce only small changes in actual heart rate.

The effects of displaying physiological parameters to VR users on emotions has also been assessed in the past. Displaying cardiac activity has been reported to have an effect on fear [24,52] or various emotions [16], and affect empathy in a collaborative context [17,18, 29], while displaying both cardiac and respiratory activity induced anxiety in a stressful situation [11]. When coupled with relaxation or meditation instructions, displaying the user's actual physiological parameters [6,29,44,45] or a simulation [51] had an effect on relaxation. Outside VR, presenting heart rate-like slow vibrations on the wrist helped reduce stress [13], especially if users thought the vibrations were mapped on their actual heart rate. Similar studies have shown that belief about an physiological change induced by false heart rate display could affect user perception of a situation and cause an emotional response. For instance, such stimulation may induce an increased perception of attractiveness when confronted with pictures [53] or an increased fear of heights [37]. Taken together, these examples suggest that displaying physiological parameters could affect user emotions while our paper focuses on the effect on the perception of physical activity.

Displaying heartbeat sounds has also been shown to induce more sensation of effort during virtual weightlifting [22] and during cycling outside VR [25]. In a VR biking exergame, increased and decreased heart rate feedback had no effect on sensation of effort [9]. Taken together, this suggests that a sensation of effort could be induced using physiological parameter displays but, until now, only simulations with auditory-only and visual-only displays of cardiac activity have been investigated.

Some work has been conducted on the effect of biofeedback – which consists in measuring a physiological parameter on a user and displaying it back to them – on embodiment in embodied VR. The physiological parameters, namely heart rate [4, 49] and breathing rate [1, 2, 38], are measured on the user and displayed on the avatar in the VE. It has been reported that such experiments induced a phenomenon called body ownership illusions, which is the illusion of being the owner of a virtual body [1, 4, 38, 49]. However, the influence of displaying avatar physiological parameters on embodiment has not been assessed yet.

In summary, our work contributes to designing novel rendering techniques to represent physiological parameters in VR. We propose multi-sensory rendering techniques for both cardiac and respiratory activity where few have been proposed in the past. This involves the design of a new haptic representation for respiratory activity in VR making use of a compression belt. In addition, we explore the effect of combining physiological parameters. Finally, we investigate the impact of displaying two physiological parameters on effort sensation, which has been done only for visual-only and auditory-only display of cardiac activity, as well as the impact of displaying avatar physiological parameters on users' sense of embodiment.

3 Design of multi-sensory rendering of avatar cardiac and respiratory activity

3.1 Rationale

Several physiological parameters rise with increased exertion, like heart rate, breathing rate, body temperature and sweating [33]. To display the parameters, we decided to use all accessible sensory modalities: vision, audition and haptics, in order to involve the user as much as possible and potentially amplify the effect of our displays. Body temperature and sweating cannot be understandably represented with all three sensory modalities. Indeed, representing these parameters via auditory cues does not seem viable. Thus, we focused on parameters related to cardiac and respiratory activity.

We favored representations that resemble real life and that are diegetic, which means they are seamlessly included in the virtual environment (VE). For instance, in video games, low health can be represented both by diegetic displays (e.g. difficult gait, blood stains, etc.) and non-diegetic displays (e.g. health bar). Finally, when designing the displays, we tried to make it clear that the body of the avatar is the origin of the physiological activity.

Following these criteria, we designed the multi-sensory rendering techniques presented in Sect. 3.3. Sect. 3.2 describes the model that generates the physiological parameters as a function of avatar physical characteristics and exertion.

3.2 Physiological model

The physiological model is the part of the application that computes cardiac and respiratory activity according to the characteristics of the avatar and the effort produced by the avatar in the VE. Its design matches the exercise scenario chosen for the user studies: a walking simulation, in which the effort is linked to walking speed and ground incline. Except Sect. 3.2.1 which is specific to walking, the model can be used for other exertion scenarios. Avatar characteristics are used to adapt the physiological response of the avatar to its physical ability. They include gender, age, height, weight, fitness, and resting heart rate. The idea is that, with an avatar matching the user, a physiological response close to their own is simulated, which could increase their self-identification to the avatar. However, in our evaluations of the system, the physiological response was not adapted to the participants to allow for a reliable comparison between individuals.

3.2.1 Oxygen consumption

To compute both cardiac and respiratory activity parameters, oxygen consumption (VO_2 in $mL.min^{-1}.kg^{-1}$) is used as an intermediary value to represent effort. The link between percentage of slope and oxygen consumption during walking [43], and between speed and oxygen consumption in several populations [7] has been investigated in the past. In our model, the relationship between slope percentage, speed and oxygen consumption is considered linear from these references (Equation 1). Minimal oxygen consumption ($VO_{2;min}$) is computed with an equation for resting VO_2 proposed by Byrne et al. [8].

$$VO_{2;acti} = VO_{2;min} + 3.08 \times speed + \%slope \times 108 \qquad (1)$$

3.2.2 Cardiac activity

Cardiac activity is a cyclic activity [15]. In our system, it is modeled by heart rate (in beats per minute, *bpm*) and stroke volume, the volume of blood pumped through the body during each cycle.

A relationship that links percentage of maximal heart rate and percentage of maximal oxygen consumption [48] is used to compute heart rate. As suggested by the authors, maximal heart rate is estimated from age. As for minimal heart rate, a standard value of 80 bpm is taken [15]. The article also provides an equation for estimating maximal oxygen consumption from fitness, age, body fat percentage and gender [48]. Lastly, body fat percentage and minimal oxygen consumption are estimated from body mass index, age and gender with equations from the literature (respectively [26] and [8]).

Stroke volume (SV) rises linearly from a minimal value at rest to a maximal value at 40% to 50% of maximal oxygen consumption [33]. In our model, we chose to index this percentage on avatar fitness (40% for low fitness, 50% for high fitness). The rendering techniques presented in Sect. 3.3.1 use percentage of maximal stroke volume instead of actual value. Thus, SV ranges from 0 to 1 and minimal and maximal SV are not computed.

3.2.3 Respiratory activity

In our system, respiratory activity is modeled by breathing rate (in breathing cycles per minute, *bpm*) and tidal volume (*L*), the volume of air displaced during each cycle. Breathing rate (*BR*) is linked to ventilation (VE), the volume of air displaced per unit of time, and tidal volume (TV), the volume of air displaced during a breathing cycle: $VE = BR \times TV$ [15, 30, 33]).

The relationship between VE/VO_2 and the percentage of $VO_{2;max}$ is described in two sources [30, 33]. In our model, under 55% of $VO_{2;max}$, VE/VO_2 is considered constant and equal to $25.10^{-3} kg.min$. Between 55% and 100%, VE/VO_2 linearly rises to $37,5.10^{-3} kg.min$. These values are not adapted to the characteristics of the avatar. To enhance adaptation to the avatar, the 55% threshold is influenced by avatar fitness (55% for low fitness, and 65% for high fitness), in accordance with the descriptions made [30, 33].

Ventilation rises during exercise to supply enough oxygen to muscles. During moderate exercise, oxygen supply is mainly due to an increased tidal volume. At higher exercise levels, tidal volume tends to saturate and breathing rate rises [15, 30]. This saturation is modeled with a linear rise from TV_{min} to TV_{max} between 0% and 55% of $VO_{2;max}$. The value for TV_{min} is picked from Essentials of exercise physiology [30]. The value for TV_{max}, also named inspiratory capacity, is computed with an equation proposed by Marsh et al. [35]. Finally, breathing rate is computed from VE and TV: $BR = TV/VE$.

3.2.4 Real time update of the parameters

This section describes how oxygen consumption evolves with time. In a simple exercise scenario (Rest, Exercise at constant intensity, Rest),

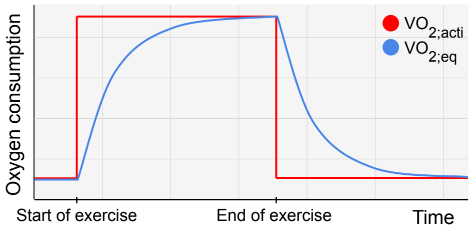

Fig. 2. Model for the evolution of oxygen consumption over time during and after exercise

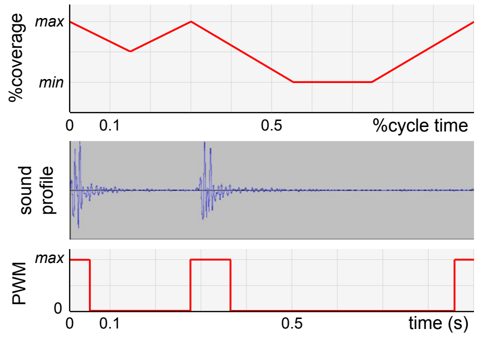

Fig. 3. Variation of Tunneling coverage, Sound profile, and PWM during a cardiac cycle

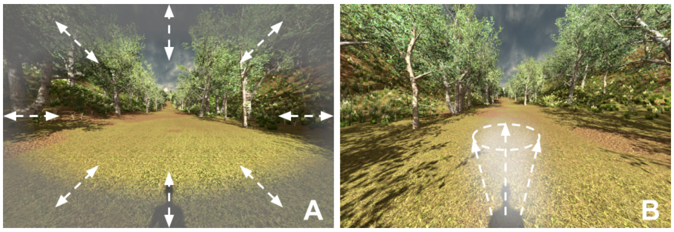

Fig. 4. Visual representations for cardiac (A) and respiratory (B) activity

the oxygen consumption quickly rises to a target value at the start of the activity, then stabilizes at constant exercise intensity, and quickly decreases at the end of exercise [33]. A similar profile is described for the evolution of heart rate during the same exercise scenario [23]. At the end of the physical exercise, the time taken to reach resting VO_2 is longer than the time it took to reach target VO_2. This phenomenon is called oxygen debt [33]. The more intense and prolonged the exercise, the more important the oxygen debt.

Our model for oxygen consumption variation is reported in Equation 2. $VO_{2;eq}$ is the oxygen consumption used to compute the physiological parameters at each frame. $VO_{2;acti}$ is the target oxygen consumption which corresponds to the current physical activity. The curve for $VO_{2;acti}$ and $VO_{2;eq}$ for a simple exercise scenario is shown in Fig. 2. Because no quantitative indications are given for convergence time in the descriptions reported, α is chosen so that the convergence time is adapted to our simulation, that is about 20 seconds. To model oxygen debt, when $VO_{2;acti} < VO_{2;eq}$, α is reduced according to an average for the past physical activity. The longer and the more intense the exercise, the longer recuperation time (up to 4 times as long).

$$VO_{2;eq} = VO_{2;eq} + (VO_{2;acti} - VO_{2;eq}) \times \alpha \times \Delta t \tag{2}$$

To summarize the model, each frame, $VO_{2;acti}$ is computed from speed and ground incline (Sect. 3.2.1), $VO_{2;eq}$ is updated to converge towards $VO_{2;acti}$ (Equation 2), and the physiological parameters are computed from $VO_{2;eq}$ (Sect. 3.2.2 and Sect. 3.2.3). The scripts that control the physiological displays read the current value for the parameters at the start of each cardiac/breathing cycle and adapt the display in accordance. The scripts that communicate with the haptic devices are executed on separate threads to avoid overloading the main thread.

3.3 Multi-sensory physiological display

3.3.1 Cardiac activity

During a cardiac cycle, two sounds are audible at auscultation [15]. In our system, all representations for cardiac activity comprise two of these "sub-beats" per cardiac cycle (see Fig. 3). The duration between the two sub-beats is a third of the total duration of the cycle. The duration of a cycle is based on the value for heart rate. The value for stroke volume (SV) influences how present each modality is made to the user. For a value of 0, each representation is barely perceptible, while for a value of 1, the representations are very present.

In terms of visual display, cardiac activity is represented by a gray (#6f6f6f, alpha=0.8) circular peripheral overlay (Fig. 4, A). It is inspired by first person perspective shooting video games in which low health is often represented by a red peripheral overlay. Gray was chosen instead of red because we anticipated that red could induce anxiety and we judged gray as more neutral. For each sub-beat, the overlay shrinks and then expands again outside the view. The higher the stroke volume, the more the overlay occludes the user's field of view at each sub-beat, and the more visible it is when expanded. This representation is implemented by using a Unity package called VR Tunnelling Pro. The Tunnelling component is used on the camera, and the coverage parameter is used to occlude more or less of the user's field of view. Coverage varies following the curve shown on Fig. 3, where $min = 0.2$ and $max = 0.5$ for $SV = 0$, and $min = 0.3$ and $max = 0.7$ for $SV = 1$. The local minimum between the two sub-beats is $(min + max)/2$.

The auditory representation for cardiac activity is a heartbeat sound, which profile is shown on Fig. 3. The sound corresponding to a cycle comprises two sub-beats. The higher the stroke volume, the louder the sound. The duration of the two sub-beats does not vary with heart rate.

The haptic representation for cardiac activity consists in delivering vibrations with a wristband (Fig. 1, D). We chose the wrist area instead of the chest or carotid because it was more convenient and safer. The wristband is composed of a circular piezoelectric actuator ($R = 6mm$) held by a fastening band adaptable to users' wrist size. The actuator is powered and controlled by an Arduino Mega. The frequency of vibrations was chosen to be around $300Hz$, which is comprised in the range frequencies for optimal sensitivity [28]. A cardiac cycle is represented by two vibrations. Vibration intensity is controlled with Arduino's Pulse Width Modulation (PWM). The profile of PWM over cardiac cycle time is plotted on Fig. 3. The maximal value for PWM varies linearly as a function of stroke volume: 160 for $SV = 0$, 220 for $SV = 1$. As shown on the plot, PWM reaches maximal value before the sound is played. This constant $0.04s$ delta of time is designed to account for the time it takes for the actuator to reach peak vibration intensity. The duration of vibrations does not vary with heart rate.

3.3.2 Respiratory activity

A respiratory cycle is divided in two phases, inspiration and expiration. Each of these phases takes a varying portion of the respiratory cycle among individuals [30]. In the chosen representation, an inspiration takes 0.45 of a cycle's duration while expiration takes 0.55, which are common values [39]. The duration of a cycle is based on the breathing rate computed by the physiological model.

Respiratory activity is visually represented by a white vapor cloud that appears, grows and vanishes in front of the avatar's mouth during expiration (Fig. 4, B). The vapor cloud is rendered using Unity's particle system. The system emits semi-transparent white circular particles in a conical shape in front of the avatar's mouth. The noise module was activated in order to make particle motion more natural. Particle velocity decreases during its lifetime. Particle alpha increases before 20% of its lifetime, and decreases after 30%. The duration of particle emission corresponds to the duration of expiration. Air flow ($flow = TV/t_{exp}$) is mapped to emission velocity, which controls the size of the

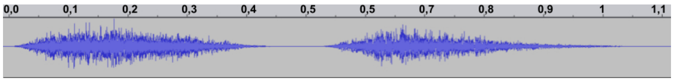

Fig. 5. Sound profile for a short inspiration (450ms) followed by a short expiration (550ms)

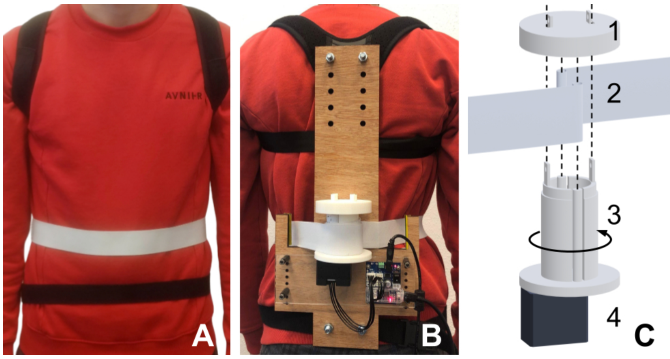

Fig. 6. Compression belt viewed from the front (A), the back (B), and closeup view of the device (C) including the motor (4), the elastic band (2) and its support (1 and 3)

cloud, and the number of particles emitted.

The audio representation is a breathing sound recorded with a microphone (view sound profile on Fig. 5). To be perceptible by users, the sound is louder than a real breathing sound. Shorter sounds, which are played when breathing rate is higher and thus for higher levels of effort, were designed to evoke more breathlessness. The higher the tidal volume, the louder the sounds.

The haptic representation for respiratory activity is performed with a compression belt shown in Fig. 6. This device is composed of static elements including a wooden plate attached to the user's back with a posture correction back brace on top and a belt at the hip level (both in black on the picture). On the wooden board are placed a U2D2 Power Hub Board and a XM430-W350 servomotor. A 3D printed support ($R0 = 2.25cm$) is screwed on the motor. It holds the two ends of an elastic band ($k = 57.9N/m$, $length = 1.5m$, $thickness = 1mm$) and allows the motor to wrap it when it spins. Both the support and the elastic band are shown in white on the picture. The belt, controlled by the application, can deliver pressure stimuli on the user's waist.

Two modes of control were considered to represent respiratory activity using this device. The first one, *wrapExpire*, consists in gradually wrapping the band during avatar expiration, which delivers a pressure stimulus, and unwrapping it during avatar inspiration. In this mode, the movement of the band simulates the virtual movement of the avatar's stomach performing abdominal breathing. The second mode, *wrapInspire*, is the opposite: the band is wrapped during inspiration and unwrapped during expiration. This mode can be interpreted as the feeling of tension caused by pressure accumulation in the body during inspiration and the feeling of relief caused by expiration. No matter the mode, a calibration phase allows the motor to wrap the band until the torque reaches a threshold value corresponding to the band sitting on the user's stomach. This initializes the resting length of the band.

The servomotor is controlled in velocity by the application. Commands for velocity are constant. For *wrapInspire*, inspiration velocity is positive (wrap) and expiration velocity is negative (unwrap). The higher the percentage of maximal tidal volume, the tighter the band is wrapped during inspiration. The tightness corresponding to minimal and maximal tidal volume were empirically chosen so that the compression is perceptible, comfortable and variable enough. Thus, for a given user, the value for velocity during inspiration depends both on inspiration time and tidal volume: $velo = target\_position(TV)/t_{insp}$. For a waist size of $92cm$, motor velocity is $15.8rpm$ for 10% slope, $27rpm$ for 20% slope, and $38.5rpm$ for 30% slope. The value for velocity during expiration is computed from current position and expiration time $velo = (rest\_pos - curr\_pos)/t_{exp}$. For *wrapExpire*, the same control is performed but inspiration and expiration controls are swapped.

4 Study 1: Influence of Cardiac Activity Displays on User Experience

Sect. 3 described the model generating the physiological parameters and the multi-sensory rendering techniques used to display them. The three following sections aim to assess the effect of such techniques on user experience.

The first study focused on the representation of cardiac activity. It investigated the influence of the different sensory modalities on several dimensions of user experience (effort sensation, embodiment, cybersickness, etc.) during the observation of a virtual walk. Participants were presented with 5 conditions for the representation of cardiac activity: visual representation only (*vis*), auditory-only (*aud*), haptic-only (*hap*), multi-sensory (visual-audio-haptic) (*mul*), and a control condition with no representation of cardiac activity (*con*).

4.1 Participants

A total of 30 volunteers were included for this study (14 men, age = 30.4 ± 10.3 years). They were almost all novice users of VR, were naive about the purpose of the experiment and had normal or correct to normal vision. They were not compensated for their participation. For all studies, participants were either researchers from the Inria Rennes research center recruited through grouped emails or volunteer medical staff from the University Hospital of Rennes (CHU Rennes). Each participant tried all of the conditions, which were counterbalanced using Latin square ordering. This implies that participants were included in 1 of 5 groups that determined the order of conditions.

4.2 Measurements

For each condition, measurements included the sensation of effort, the sense of embodiment, the sensation of walking, cybersickness, sensation of comfort and user preference. Embodiment was measured using the questionnaire proposed by Peck and Gonzalez-Franco [41]. It was completed following the suggestions of the authors for generic VR simulations. The questionnaire measures 4 sub-components of embodiment: appearance, response, ownership, and multi-sensory, which are scored on a 7-point scale. Cybersickness was measured using the Virtual Reality Sickness Questionnaire [31] which outputs a 0 to 100 score. Three additional items were added at the end of the questionnaire: I felt like I was walking ; I felt like I was making an effort ; The simulation was overall comfortable. The items are valued on a 7-point Likert Scale (1 = Strongly disagree, 7 = Strongly agree).

A general questionnaire consisted of two additional items. Participants had to rank the conditions according to their sensation of effort and their preference. Participants' comments were also written down.

4.3 Hypotheses

As previous work has shown that providing fake heart rate feedback induced a sensation of effort in other scenarios [22, 25], we expected that our displays would do as well and decided to test if walking sensation could be affected too. Past work has shown that displaying the user's physiological activity on their avatar increased the sense of embodiment [1,2,4,38,49]. We made the assumption that providing the user with their avatar's activity would also benefit embodiment. Finally, we expected that using multiple sensory modalities would be more involving for users, as it was shown for haptics and audio [10], and thus amplify the effects of our displays. Therefore, we expected effort and walking sensation, embodiment and preference to be higher for the multi-sensory condition than for the uni-sensory conditions. We also expected these measures to be higher for the uni-sensory conditions than for the control condition. As for comfort and cybersickness, we wanted to confirm that our system would remain comfortable even with additional sensory stimulation.

4.4 Procedure

In all three studies, an HTC Vive Pro head-mounted display (HMD) provided visual and audio cues from the virtual environment (VE).

Table 1. Physiological parameters during a simulation

	Resting	10% slope	20% slope	30% slope
HR (bpm)	80	100	120	140
SV	0	0.5	0.95	1
BR (bpm)	10	12	19.5	27
TV (L)	0.5	1.6	2.2	2.4

Computer specifications were the following: Intel Core i7-11800 CPU, 16GB RAM, NVIDIA GeForce RTX 3070 Laptop GPU. The participants were seated and viewed the VE in first person perspective with the HMD. Only the movements of the head were mapped to the 3D view and the head of the avatar. The participants were attributed by the experimenter with an avatar that approximately corresponded to their physical appearance in terms of gender, skin tone, height, corpulence and hair color. In order to give more cues on the movement of the avatar, a clear shadow was projected on the ground in view of the user (Fig. 1, A). Camera oscillations due to the walking animation were damped to limit cybersickness.

In order to induce a sensation of effort, we chose to make the physiological parameters rise during a walking simulation. To do so, the avatar walked straight up a hill divided in 3 sections of equal length, each of which with a different level of slope: 10%, 20% and 30%. Walking up the hill, the physiological response of the avatar rose from resting to a first level of effort and stabilized, then from the first to a second and from the second to a third. At the end of the hill, the ground became flat again, the avatar stopped walking, and the physiological response went down to resting. The physiological response was not based on participants' physical traits to allow for a reliable comparison between individuals. The characteristics used as input for the physiological model were chosen so that the change in physiological response could be easily identified by participants. The approximate value for the displayed parameters are presented for each level of effort in Table 1.

Participants were explained the procedure and signed a consent form. Then, the wristband was installed on their dominant hand, followed by the HMD (Fig. 1, B). Participants then sat on a chair and the first condition started. The sitting position was chosen as it is a common gaming position which does not induce much sensation of effort and could benefit from our system. Also, it induces as much embodiment as standing when observing a walking simulation and is more comfortable [46]. Participants were told that, during the simulations, they could look around and had to focus on their sensations and relationship with their avatar. Before the first condition, participants observed the avatar in front of a mirror for 1 minute in order to familiarize themselves with the virtual body. The avatar then started walking, and the physiological parameter display corresponding to the first condition was turned on. Between each condition, participants took off the HMD, a laptop was handed out to them and they filled in the questionnaire corresponding to the condition. After the last condition, they filled in the corresponding questionnaire and answered the general questionnaire which consisted in ranking the conditions. The simulation for a condition lasted 2 minutes and 30 seconds and the overall experiment lasted 40 to 45 minutes. All of the procedures reported in this article were approved by the ethical committees from the CHU Rennes and Inria lab.

4.5 Results

The results for effort sensation, walking sensation, and the four subcomponents of embodiment (appearance, response, ownership and multi-sensory) for study 1 are reported on Fig. 7. We used repeated measures two-way ANOVA to analyze the results. When the Shapiro-Wilk normality test did not validate the normality assumption, we used the Aligned Rank Transform (ART) model before performing the ANOVA. Post-hoc tests were performed using the Estimated Marginal Means (emmeans) method. Non-significant results are not reported.

The ANOVA for effort sensation showed a significant effect of condition ($F_{3.08,77.04} = 5.99$, $p = 0.003$, $\eta_p^2 = 0.193$). Post-hoc tests showed that the multi-sensory condition performed better than the visual ($p < 0.001$) and control conditions ($p = 0.005$). The ART ANOVA for response

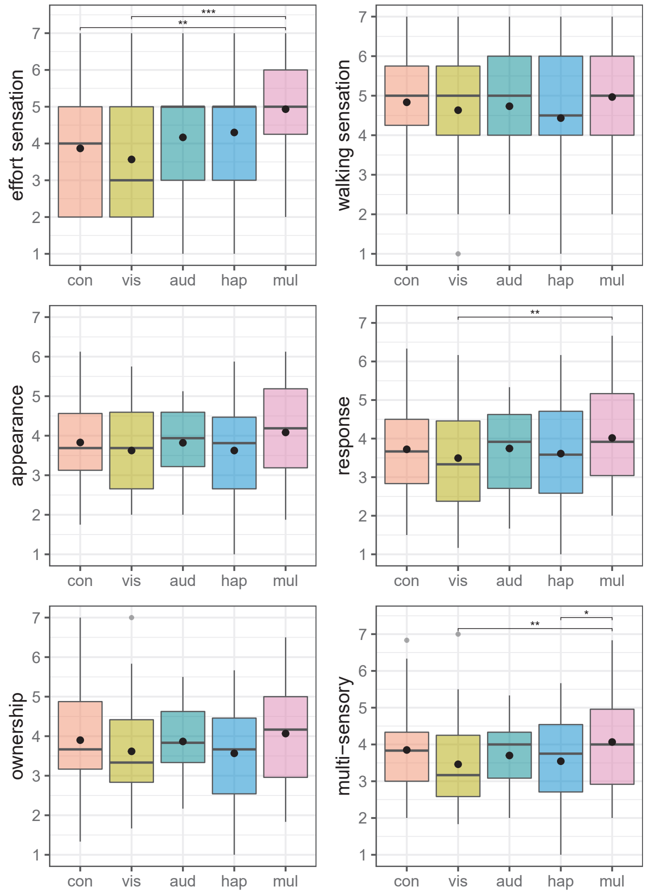

Fig. 7. Study 1: Effort sensation, Walking sensation, and the 4 subcomponents of Embodiment (Appearance, Response, Ownership, Multisensory) for each condition

showed a significant effect of condition ($F_{4,100} = 3.20$, $p = 0.016$). Post-hoc tests showed that the multi-sensory condition performed better than the visual condition ($p = 0.008$). The ANOVA for multi-sensory showed a significant effect of condition ($F_{3.22,80.56} = 3.84$, $p = 0.033$, $\eta_p^2 = 0.133$). Post-hoc tests showed that the multi-sensory condition performed better than the visual ($p = 0.008$) and haptic conditions ($p = 0.036$).

Cybersickness was low ($M = 13.9$, $SD = 11.8$, 100-point scale), and comfort was high ($M = 5.55$, $SD = 1.48$, 7-point Likert scale). There was no significant effect of condition on either variable, which confirmed our expectation on comfort. The plots for both variables are not reported in the figures.

The ranking of the conditions for effort sensation and personal preference are reported on Fig. 8. To assess the impact of the conditions on the two rankings, Friedman tests were performed. Post-hoc tests were performed using the Wilcoxon signed-rank method.

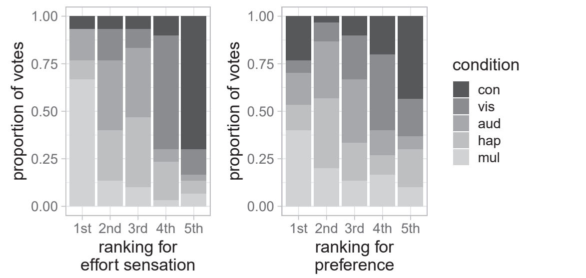

Fig. 8. Study 1: Condition ranking for Effort sensation and Preference

The Friedman test for effort sensation showed a significant effect of condition ($p < 0.001$). Post-hoc tests showed that the multi-sensory condition was ranked significantly higher than the control ($p < 0.001$), visual ($p < 0.001$) and haptic ($p = 0.015$) conditions. The audio condition was ranked higher than the visual ($p = 0.004$) and control ($p = 0.002$) conditions. The haptic condition was ranked higher than the control condition ($p = 0.016$). Rankings for personal preference showed that the multi-sensory condition was preferred by most participants (40%). The control condition was ranked last by 43% of participants, but was also ranked first by 23% of them. The Friedman test confirmed the effect of condition on personal preference ($p = 0.006$). Post-hoc tests showed no significant difference between pairs of conditions.

Overall, these results suggest that our multi-sensory display of cardiac activity can increase the sensation of effort. These results are discussed in Sect. 7. In the following, we investigate the effects of our rendering technique for respiratory activity.

5 Study 2: Influence of Respiratory Activity Displays on User Experience

The second study is the equivalent of the first study (Sect. 4) with respiratory activity instead of cardiac activity. We investigated the same conditions for the display of avatar respiratory activity (*vis*, *aud*, *hap*, *mul* and *con*). Measured variables and procedure were the same as for study 1 (see Sect. 4.2 through Sect. 4.4). In addition to the measured variables, user breathing was recorded using the microphone present on the HTC Vive Pro. We made the same hypotheses for study 2 as for study 1 (see Sect. 4.3) with the addition of a synchronization of user breathing with avatar breathing, in accordance with previous work [14, 54]. The second study was preceded by a pilot study that helped choose which of the two compression modes to use to represent breathing via haptics using our compression belt.

5.1 Pilot study: Compression mode for breathing display

A pilot study was conducted in order to choose the most suitable haptic representation mode for respiratory activity. A sample of 12 volunteers were included in the study (7 males, $age = 26.8 \pm 4.5$ years). They were all familiar with VR.

Participants were presented with the walking simulation without the hill. Multi-sensory (visual, auditory and haptic) representation of respiratory activity corresponding to moderate exercise was displayed to them. They were told that two ways to display breathing in VR (*wrapInspire* and *wrapExpire*, see Sect. 3.3.2) were going to be presented to them and that they had to judge the consistency between the cues and pick their favorite representation. They were not told the difference between the conditions. The two conditions were successively presented to the participant for 1 minute each. Conditions were counterbalanced across participants. At the end of the 2 minutes, they picked the condition they preferred in the simulation with a Vive controller. They then took off the HMD and filled in a 4-item questionnaire.

With the first two items, participants rated on a 7-point Likert the consistency of visual, auditory and haptic cues that represented breathing in condition 1 and 2. For the third item, they had to choose the condition they preferred between condition 1 and 2. Finally with the fourth item, they rated on a 3-point scale (Not at all, Somewhat, Very) their confidence in their previous answer. In addition to the questionnaire, participants were asked to give a justification for their answers.

Results showed that consistency was relatively high for both conditions ($M = 4.67$ for *wrapExpire* and $M = 4.83$ for *wrapInspire*). Since the normality assumption was not validated for consistency, an ART ANOVA was performed. It showed no significant effect of condition or group ($p = 0.96$, $p = 0.40$). 6 participants preferred one condition and 6 preferred the other. For both conditions, 1 participant was moderately confident in their choice and no participant was indecisive. Since the results were perfectly balanced, no statistical analysis was performed.

From the scores for consistency and participants' justifications, we conclude that the two ways of interpreting our haptic representation for respiratory activity are about equally represented in the population.

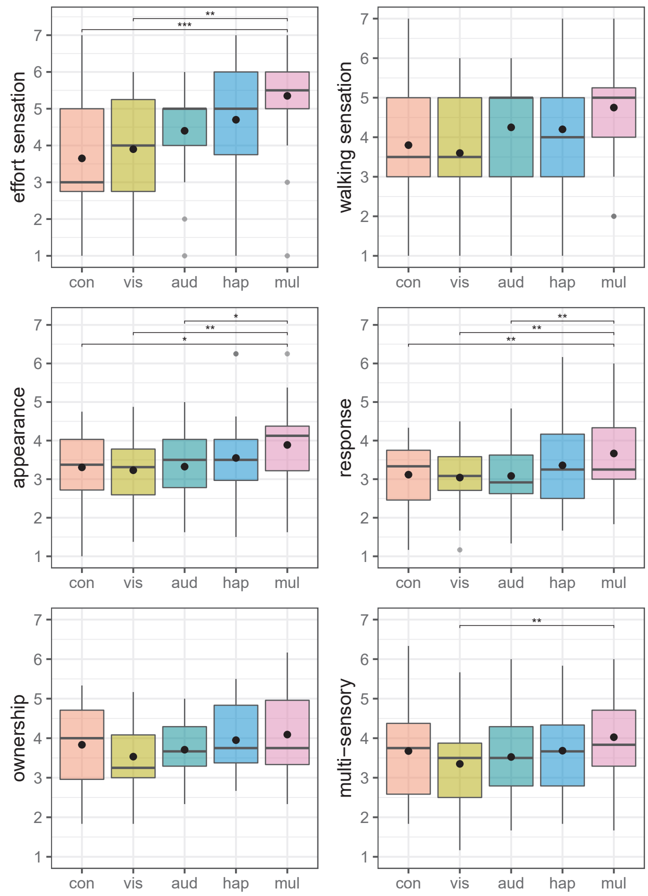

Fig. 9. Study 2: Effort sensation, Walking sensation, and the 4 sub-components of Embodiment (Appearance, Response, Ownership, Multi-sensory) for each condition

Since the score for consistency was high for both modes with no significant difference, choosing one mode over the other should not make much difference on participants' perception of the haptic stimulation. The equal number of votes for both modes does not allow to indicate a preferred mode in the population.

These results led us to choose mode *wrapInspire*, because we favor one interpretation over the other: the wrapped band represents the tension in the body when the lungs are filled with air.

5.2 Main study

5.2.1 Participants

A total of 20 volunteers were included for the second study (9 men, age = 27.9 ± 7.7 years). Participants for this study were not the same as for study 1. About half the participants was not familiar with VR, while the other half was somewhat to very familiar. They were all naive about the purpose of the experiment and had normal or correct to normal vision. They were not compensated for their participation. Each participant tried all the conditions and like for study 1, conditions were counterbalanced using Latin square ordering.

5.2.2 Results

The results for effort sensation, walking sensation, and the four sub-components of embodiment (appearance, response, ownership and multi-sensory) for study 2 are reported on Fig. 9. The same analysis as the one for study 1 was performed.

The ANOVA for effort sensation showed a significant effect of condition ($F_{2.65,39.82} = 5.98$, $p = 0.008$, $\eta_p^2 = 0.285$). Post-hoc tests showed that the multi-sensory condition induced more effort sensation than the control ($p < 0.001$) and visual conditions ($p = 0.004$).

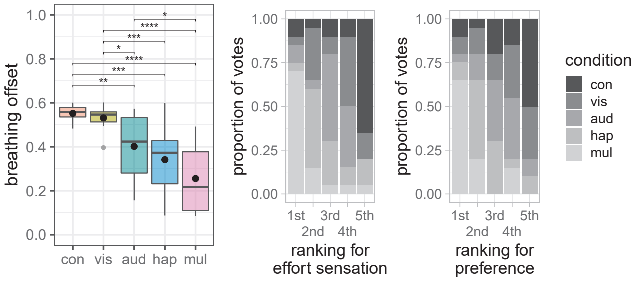

Fig. 10. Study 2: Offset between user breathing and simulated breathing for each condition, and condition ranking for Effort sensation and Preference

The ANOVA for appearance showed a significant effect of condition ($F_{2.94,44.17} = 4.49$, $p = 0.024$, $\eta_p^2 = 0.230$). Post-hoc tests showed that the multi-sensory condition performed better than the control ($p = 0.018$), the visual ($p = 0.005$) and auditory conditions ($p = 0.025$). The ANOVA for response showed a significant effect of condition ($F_{3.03,45.41} = 5.62$, $p = 0.007$, $\eta_p^2 = 0.273$). Post-hoc tests showed that the multi-sensory condition performed better than the control ($p = 0.008$), the visual ($p = 0.002$) and auditory conditions ($p = 0.004$). The ART ANOVA for multi-sensory showed a significant effect of condition ($F_{4,60} = 3.82$, $p = 0.008$). Post-hoc tests showed that the multi-sensory condition performed better than the visual condition ($p = 0.005$).

Cybersickness was low ($M = 8.96$, $SD = 11.4$), and comfort was high ($M = 5.53$, $SD = 1.31$). There was no significant effect of condition on either variable, which confirmed our expectation on comfort.

The audio recordings for participants' breathing were manually annotated in order to identify the start of all breathing cycles. The second half of the recordings was lost due to a technical problem, so only the recordings for the first 10 participants were available for analysis. The time of the participants' breathing cycles was compared to the time of the displayed breathing cycles. The metric is the sum of the time offsets between one breathing cycle and the closest cycle in the other sequence, for both sequences. The result is normalized by the duration of the recording. The metric is a positive value indicating perfect synchronization for a value of 0. Even if no breathing was displayed to the user in the control condition, the metric is computed in order to give a value for "undirected breathing" that can be compared to the other conditions. A lower value than the control condition means that some level of synchronization is observed.

The results for the offset between user breathing and simulated breathing are reported on Fig. 10. The ANOVA showed a significant effect of condition on synchronization ($F_{1.61,8.07} = 21.06$, $p = 0.003$, $\eta_p^2 = 0.808$). Post-hoc tests showed that breathing offset was lower for the multi-sensory condition than for the auditory ($p = 0.012$), visual ($p < 0.001$) and control conditions ($p < 0.001$). Breathing offset for the haptic condition was lower than for the visual ($p < 0.001$) and control conditions ($p < 0.001$). Breathing offset for the auditory condition was lower than for the visual ($p = 0.032$) and control conditions ($p = 0.009$). The visual condition did not induce any significant synchronization since no difference in offset was reported with the control condition.

The ranking of the conditions for effort sensation and personal preference are reported on Fig. 10. Like for study 1, a Friedman test was performed to assess the impact of condition on the rankings and post-hoc tests were performed using the Wilcoxon signed-rank method.

Rankings for effort sensation show that the multi-sensory condition comes first and the control condition comes last for a majority of participants. The Friedman test confirmed the effect of condition on ranking for effort sensation ($p < 0.001$). Post-hoc tests showed that the multi-sensory condition was ranked higher than the others conditions (*vis*: $p = 0.031$, *aud*: $p = 0.022$, *hap*: $p = 0.015$, *con*: $p = 0.012$).

The multi-sensory condition is preferred by a majority of participants. The Friedman test confirms the effect of condition on personal preference ($p < 0.001$). Post-hoc tests showed that the multi-sensory condition was ranked higher than all of the other conditions (*vis*: $p = 0.021$, *aud*: $p = 0.036$, *hap*: $p = 0.047$, *con*: $p = 0.012$).

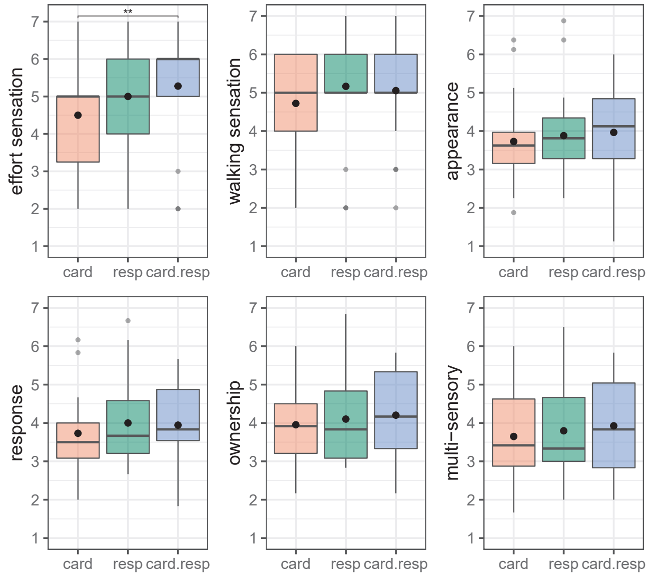

Fig. 11. Study 3: Effort sensation, Walking sensation, and the 4 subcomponents of Embodiment (Appearance, Response, Ownership, Multi-sensory) for each condition

Overall, these results suggest that our multi-sensory display of respiratory activity can increase the sensation of effort, induce a synchronization of user breathing, and seems to have a moderate impact on the sense of embodiment. These results are discussed in Sect. 7. In the following, we investigate the effects of combining the rendering techniques for both physiological parameters.

6 Study 3: Influence of Combining Displays of Cardiac and Respiratory Activity on User Experience

The third study assesses the impact of combining the multi-sensory display for both physiological parameters on user experience. Participants were presented with 3 conditions: multi-sensory display of cardiac activity (*card*), respiratory activity (*resp*), and a combination of both (*card.resp*). We hypothesized that combining the multi-sensory display for both physiological parameters would be beneficial to user experience. We were expecting the user experience to be better for condition *card.resp* than for the other two. The procedure and measurements were the same as for study 1 (see Sect. 4.2 through Sect. 4.4).

6.1 Participants

A total of 18 volunteers were included for this study (11 men, age = 27.1 ± 7.3 years). Participants were not the same as for study 1 and 2. About half the participants was not familiar with VR, while the other half was somewhat to very familiar. They were not compensated for their participation. Each participant tried all the conditions. Like for study 1, conditions were counterbalanced using Latin square ordering.

6.2 Results

The results for effort sensation, walking sensation, and the four subcomponents of embodiment (appearance, response, ownership and multi-sensory) for study 3 are reported on Fig. 11. The same analysis as for study 1 and study 2 was performed.

The ART ANOVA for effort sensation showed a significant effect of condition ($F_{2,30} = 6.61$, $p = 0.004$). Post-hoc tests showed that condition *card.resp* induced more sensation of effort than condition *card* ($p = 0.003$).

Cybersickness was low ($M = 9.97$, $SD = 9.78$), and comfort was high ($M = 5.68$, $SD = 1.36$). There was no significant effect of condition on either variable, which confirmed our expectation on comfort.

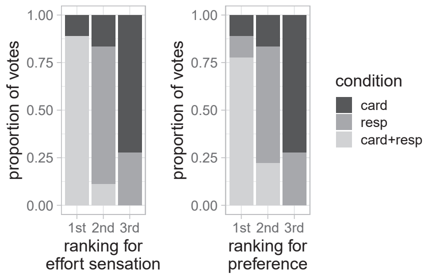

Fig. 12. Study 3: Condition ranking for Effort sensation and Preference

The ranking of the conditions for effort sensation and personal preference are reported on Fig. 12. The Friedman tests confirmed the effect of condition on both rankings ($p < 0.001$ and $p < 0.001$). Post-hoc tests showed that condition *card.resp* induced more effort sensation than conditions *card* ($p < 0.001$) and *resp* ($p < 0.001$). Condition *card.resp* was also preferred over conditions *card* ($p = 0.002$) and *resp* ($p = 0.004$).

Overall, these results suggest that combining both our multi-sensory displays has a positive impact on effort sensation. Since the combination of both physiological parameters is also preferred by participants, it seems to be a viable technique to convey a sensation of effort.

7 Discussion

This section provides a discussion based on the three studies' results and analysis. In the studies, we investigated the influence of our multi-sensory rendering techniques on several aspects of user experience such as effort sensation and embodiment. The first and second study focused respectively on displaying the avatar's cardiac activity and respiratory activity. The third study explores the effect of combining both displays.

Overall, the results from the first two studies showed our rendering techniques to be most effective on effort sensation. In particular, a display for cardiac activity gathering visual, auditory and haptic cues induced more effort sensation than the visual-only, haptic-only displays and no-display conditions in study 1. In study 2, multi-sensory display of respiratory activity induced more effort sensation than all uni-sensory conditions and than the control condition. Study 3 shows that combining multi-sensory displays for both cardiac and respiratory activity is beneficial to the sensation of effort. More generally, all variables show a higher or equivalent score of condition *card.resp* compared to the other two. This confirms that the 6 different physiological displays did not over-stimulate participants.

The two visual representations were the least effective of the three modalities since no significant difference was reported between the visual and control conditions in the first two studies for all variables measured. Participants' spontaneous comments, which were not systematic, and previous work from the literature provided leads of explanations. In a study comparing the different combinations of sensory modalities for heart rate feedback, Chen et al. reported the combination of audio and haptics to be the most preferred, and their visual representation to be rather distracting [10]. Even if our display for cardiac activity is different, the same effect could explain our results in part, as suggested by 1 participant. In addition, our representation may have been hard to interpret on its own, as suggested by 2 participants, or even hard to perceive, it being in peripheral vision, as suggested by 4 participants. This may explain why it performed rather badly on its own but did not impair the multi-sensory condition too much. More generally, representing a body function without visual manifestation like cardiac activity via vision may be contradictory and destined to fail. Similar explanations may be brought up to explain the poor performance of the visual representation of respiratory activity. The provided explanations are speculative, further studies should be conducted to confirm them.

In study 2, appearance and response, two of the four sub-components of embodiment, were significantly higher for the multi-sensory condition than for the auditory, visual and control conditions. Interestingly, appearance is usually influenced by avatar appearance [41] while our rendering techniques do not modify appearance. Appearance is highly correlated with response [41], the second sub-component of embodiment on which our multi-sensory display has a positive impact. Most questions related to motor control and agency contribute to the response score [41], which shows that the multi-sensory condition may have a positive impact on these factors. This may be explained in part by the fact that the haptic representation for breathing forces a match between virtual avatar motion and real user motion by inducing a synchronization of user breathing. In study 1, embodiment sub-scores are lower, although non-significantly, for the visual and haptic conditions than for the multi-sensory condition. The bad performance of the visual condition may be due to it being distracting. As for haptics, a possible interpretation suggested by 2 participants is that the stimulation reminded them too much of their real body since no other cue ties the stimulation to the VE. Embodiment sub-scores seem rather consistent between the studies. Previous work evaluated embodiment during the observation of a virtual walk in seated position [32, 46]. Even if the measures are not exactly the same, our results seem to be lower. This could be explained by the fact that participants were immersed in the VE during 2 minutes 30 in our studies while in previous work they were during 4 minutes [32,46]. This is supported by comments from 6 participants across the three studies who reported getting used to the simulation between the conditions, suggesting that 2 minutes 30 was not sufficient to reach maximal embodiment.

Differences in mean score for effort and walking sensation can be observed between the studies. In particular, the results for the control condition, in which no physiological parameter is displayed, are lower in study 2 than study 1. This may be explained by disparities among the populations, in terms of familiarity with VR for instance. These differences make it difficult to draw comparisons between the studies.

8 Conclusion and perspectives

In this paper we explored the multi-sensory display of self-avatars' physiological state in Virtual Reality (VR), as a means to enhance user experience and the relationship between user and avatar. Our approach consisted in designing and combining a coherent set of visual, auditory and haptic cues to represent the avatar's cardiac and respiratory activity. We notably introduced a novel haptic technique to represent respiratory activity using a compression belt reproducing abdominal movements that occur during a breathing cycle. We conducted three user studies that identified of positive effect of using our multi-sensory rendering technique for cardiac activity-only, respiratory activity-only, and of combining both on effort sensation. Multi-sensory display of respiratory activity also had a positive effect on appearance and response, two sub-components of embodiment.

In the future, other techniques could be explored to represent cardiac and respiratory activity in VR, in particular visual representations for both parameters and haptic representations for cardiac activity. Indeed, visual-only displays did not significantly enhance user experience and haptic and visual displays were judged disturbing by a few participants. Given these limitations, complementary user studies could be performed to identify if bi-sensory displays would perform better than our multi-sensory displays. Further studies could explore the effect of providing a physiological response adapted to participants' physical characteristics, as this aspect of the physiological model was not investigated in our studies and as some participants commented spontaneously. Measuring the user's physiological activity could prove useful in order to adapt the resting activity and to characterize the effect of our system. Additional work could introduce new physiological parameters such as body temperature and sweating. The effect of our rendering techniques could also be investigated with non-static users or for practical application scenarios such as sports training or rehabilitation in VR.

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