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Effects of voluntary heart rate control on user engagement and agency in a virtual reality game

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Abstract

It has been demonstrated that virtual reality (VR) exposure can affect the subjective experience of different situations, cognitive capabilities or behavior. It is known that there is a link between a person's physiological state and their psychological self-report and user experience. As an immersive experience can affect users' physiological data, it is possible to adapt and enhance the content of a virtual environment in real-time base on physiological data feedback (biofeedback). With the rapid evolution of the physiological monitoring technologies, it is now possible to exploit different modalities of biofeedback, in a cheap and non-cumbersome manner, and study how they can affect user experience. While most of the studies involving physiological data use it as a measuring tool, we want to study its impact when direct and voluntary physiological control becomes a mean of interaction. To do so, we created a two-parts protocol. The first part was designed to categorize the participants on their heart rate control competency. In the second part of the study, we immersed our participants in a VR experience where they must control their heart rate to interact with the elements in the game. The results were analyzed based on the competency distribution. We observed consistent results between our competency scale and the participants' control of the biofeedback game mechanic. We also found that our direct biofeedback mechanic is highly engaging. We observed that it generated a strong feeling of agency, which is linked with users' level of heart rate control. We highlighted the richness of biofeedback as a direct game mechanic, prompting interesting perspective for personalized immersive experiences.

Keywords Virtual reality · Biofeedback · User engagement · Agency · User study

1 Introduction

Using physiological data to influence an interactive experience is called biofeedback, which is simply defined by Riedl et al. (2014) as "systems that recognize the physiological state of the user and that adapt, based on that information, in real-time." The usage of physiology in virtual reality (VR) has been studied in order to bring more out of the experience (Muñoz et al. 2016; Dey et al. 2017). If the general consensus seems to point toward the fact that the usage of physiological biofeedback can increase user engagement in VR experiences, it has some limitations when it is not fully taken into account (Dekker and Champion 2007; Houzangbe et al. 2018a). Most of the studies focusing on biofeedback in VR use it as a passive tool to understand the user's state or adapt the environment. Biofeedback is rarely an active game mechanic that the user consciously influence. That is why we want to study how a biofeedback game mechanic, mandatory to complete the game, can influence user experience in immersive virtual environments (IVE).

To do so, we built a two-part study, the first part consists of determining the ability of the participants to control their own heart rate and classifying them in different skill groups. The second part of our experience will expose the participants to an IVE where they have to voluntarily control their heart rate to complete the game. We analyze the participants reported feeling of engagement and sense of agency in regard to their competency.

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The next section presents a state-of-the-art concerning voluntary heart rate control, draws a link between the concept of physiological self-efficacy and the sense of agency and finally highlights the influence of biofeedback on user engagement. Section 3 presents the first part of our experiment (protocol and results). Section 4 presents the second part of our study (VR application, experimental design, results and discussion). Finally, Sects. 5 and 6 present a critical look at our experience and the conclusions to our work. Section 7 presents potential directions for future work.

2 Related work

2.1 Heart rate control

Heart rate is a strong indicator of the psycho-physiological state (Sarkar et al. 2014), because it is modulated in response to an emotional stimulus (stress, fear, joy). To understand the control mechanism behind it, multiple studies have been conducted (e.g., Davies and Neilson 1967; Obrist et al. 2017). Sroufe (1971) tries to observe, with a series of experiments, the effects of breathing depth and rhythm on heart rate variability. During these experiments, the participants must breathe following a predetermined pattern (slow, regular or fast) and a defined depth (shallow or regular). The results of his experiments show that breathing rhythm does not affect heart rate, but that breathing depth does, in accordance to the works of Clynes (1960) and Westcott and Huttenlocher (1961). Moreover, Sroufe denotes that a training strategy, by instructing the participants of a series of respiratory schemes and showing the effects on the heart rate of said schemes, seems to allow the participants to acquire direct heart rate control faster.

Holmes et al. (1979) study the separated and combined effects of breathing and feedback on heart rate control. They demonstrate that it is possible to accelerate one's own heart rate with breathing. Malcuit and Beaudry (1980) highlight the ability of the participants to willingly lower their heart rate immediately after a stress inducing event that provokes an acceleration of the heart rate. The previously cited studies, as well as the ones conducted by Manuck et al. (1975) and Stephens et al. (1975), demonstrate one's ability to control one's heart rate. However, their results differ regarding the benefits of the feedback. If these studies insist on the importance of experience in heart rate control, Manuck et al. (1975) indicate that their results do not support the hypothesis that the feedback immediately facilitate voluntary heart rate control. They explain that feedback only have significant effects after the participants have been subject to multiple test sessions.

Larkin et al. (1990) try to study the effects of voluntary heart rate control on performance during a psychomotor task. They use a video game to evaluate how much the participants are capable of reducing their cardiac reaction when faced with the challenge proposed by the game, after a biofeedback training with repeated game sessions. This way they try to determine if the participants are capable of learning how to reduce their heart rate without worsening their in-game performance. Their results indicate a lower cardiac response after the training (a better ability to self-regulate their heart rate). Moreover, they also note that heart rate is generally lower for the participants with the feedback, after they benefited from multiple training sessions, which is in accordance with multiple previous works (e.g., Larkin et al. 1989; McCanne 1983). However, they note that the groups that benefit from the feedback show a worse in-game performance. They make the assumption that the participants have a hard time appropriating both mechanics at the same time. More recently, we can highlight the work of Peira et al. (2014), who study how biofeedback can help mitigate emotional response through heart rate control. They conclude that it is possible to have voluntary control over one's own heart rate and that biofeedback helps in that regard and in a better control over one's emotional response.

Nenonen et al. (2007) study how heart rate can be used to control an interactive game. In a biathlon exergame, the skiing speed is directly replaced with the participant's heart rate. The heart rate, when high, is also used to impede the player's shooting. They conclude that heart rate can be used and is a fun game mechanic. In a more recent study, Wollmann et al. (2016) evaluate how a gamified heart rate variability training experience (with biofeedback) can influence the participants' motivation and engagement in the experience and produce better results. In their game, the participants have to fly a plane using breathing techniques to keep it stable. They confirm the potential of video games for motivating players to engage in biofeedback training and perform better.

The studies presented in this section demonstrate the possibility to influence one's own heart rate, thanks to breathing mainly. They also begin to link voluntary heart rate control to interactive applications, showing how it can be used to affect user experience.

2.2 From physiological self-efficacy to agency

The sense of agency is defined as the sensation of "global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will" (Blanke and Metzinger 2009). If this definition is mainly centered around physical control, Bandura (1982) explains that physiological self-regulatory capabilities require tools of personal agency, as "people who are skeptical of their ability to exercise adequate control over their actions tend to undermine their efforts in situations that tax capabilities." There is an influence of agency and the sense of agency on self-efficacy through the capacity of control. Jeunet et al. (2018) add to that construction of the sense of agency a model dividing it into two components: the feeling of agency and the judgment of agency. They explain that the sense of agency relies on three principles, the principles of priority (the intention of action immediately precedes the action), exclusivity (one's thoughts must be the only apparent cause of the outcome) and consistency (the sensory outcome matches the predicted outcome).

Self-efficacy is the belief one has in his/her ability to achieve a task (Bandura 1982, 1993). According to Bandura (1997), self-efficacy extends all the way to physiological and emotional states. To evaluate his/her own abilities, one bases himself/herself partly on the information transmitted by his/her physiological and emotional state. The techniques that allow the regulation of emotional reactions strengthen the belief in one's ability to manage stress and generate an improvement of performance.

In a recent study, Weerdmeester et al. (2017) examine the role of physiological self-efficacy in the context of a biofeedback enhanced video game. They conduct a study with the game DEEP, a virtual reality (VR) game that uses respiratory biofeedback to help the players manage stress and anxiety. They report that the higher the feeling of self-efficacy, the lower the level of arousal. Arousal is measured using the Physiological Arousal Questionnaire (Dieleman et al. 2010), and self-efficacy using the Self-Efficacy Scale for Youth (Muris 2001). They conclude that DEEP helps the players to better regulate their emotional response. Their study is, however, to be treated carefully. Indeed, the absence of a control group in their protocol limits the conclusions they can make. Others have studied the effect of the inclusion of biofeedback in VR experiences. It is the case of Flowers (2018) which studies the effect of biofeedback on embodiment and presence. We can also note the work of Salminen et al. (2018), who present how biofeedback enhanced social meditation in VR can affect social presence and affective interdependence. All those studies highlight the interest of integrating biofeedback in VR to modulate user experience in various ways.

As demonstrated by the work of Weerdmeester et al. (2017) and Prpa et al. (2018), the sense of physiological self-efficacy influences the sense of agency in virtual environment. Moreover, it is interesting to note that the usage of biofeedback helps the users to gain a better control of their physiology, shifting their Locus of Control[1] to be more personal. Jeunet et al. (2018) suggest that a person's Locus of Control influences the sense of agency. Thus, through a change in the Locus of Control, thanks to biofeedback, it is possible to influence the emergence of the sense of agency, naturally linking physiological self-efficacy and agency.

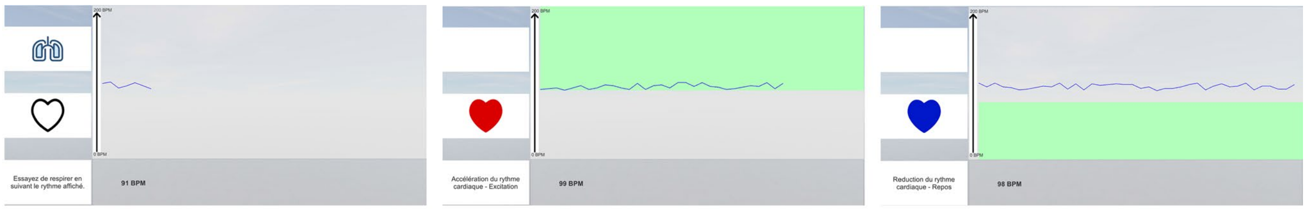
2.3 User engagement

O'Brien and Toms (2008) developed a conceptual framework to define User Engagement with technology. They characterized engagement as "a quality of user experience characterized by attributes of challenge, positive affect, endurability, aesthetic and sensory appeal, attention, feedback, variety / novelty, interactivity and perceived user control." The work of Hassenzahl et al. (2010) points toward similar yet simpler conclusions, as they divide engagement in two main categories: pragmatic qualities (usefulness and usability of the system) and hedonistic qualities (motivation, stimulation and challenge for the user). These models are mainly inspired by the Flow theory (Csikszentmihalyi 1975) which is also used by multiple researchers as a core of their model and research on user engagement (e.g., O'Brien and Toms 2010; Wiebe et al. 2014; Phan et al. 2016). It describes "the mental state of operation in which a person performing an activity is fully immersed in a feeling of energized focus, full involvement, and enjoyment in the process of the activity."

It is important to be able to adapt the level of challenge depending on the level of physiological control to create a state of flow and generate engagement. Some studies have been conducted to understand the effects of biofeedback on user engagement, for gaming (Dekker and Champion 2007; Ambinder 2011) and VR (Dey et al. 2017; Houzangbe et al. 2018a). The consensus of the studies is that the usage of biofeedback is a vector of higher engagement (Ohmoto et al. 2017; Argasiński et al. 2018). However, biofeedback generally takes the role of an additional mechanic that the user can neglect during his/her experience.

By including biofeedback to a VR experience, it is possible to strengthen the feeling of physiological self-efficacy and thus change the user's locus of control, favoring a higher sense of agency (Jeunet et al. 2018). If the integration of physiology in interactive experiences can allow to strengthen user engagement (Sra et al. 2018), the effects can, however, be limited by the lack of control of physiology. Thus, it is important to provide a personalized experience, based on competency, and study how a voluntary heart rate control biofeedback mechanic affects user experience. In our study, we first wish to develop a heart rate control competency scale. Then propose a virtual reality experience during which voluntary heart rate control is the only interaction paradigm. This study is designed to evaluate the impact

[1] A concept in psychology, proposed by Julian Rotter in 1954, describing the fact that individuals are different in their appreciation and beliefs on what determines their success in a specific activity, what happens in a given context or, more generally, what influences the course of their lives.



(a) Phase 2: breathing and accommodation **(b)** Phase 3: accelerating heart rate **(c)** Phase 3: reducing heart rate

Fig. 1 Screenshots of the application of the first study

of such a mechanic on user experience, especially on user engagement and agency.

3 Study 1: Quantifying heart rate control

To quantify one's own heart rate control competency, we developed a simple desktop application that proposes a series of heart rate control exercises. They consist in accelerating the heart rate or lowering it during 1:30 min.

3.1 Apparatus

We used a desktop PC and a Mio LINK heart rate wristband for this experiment. The Mio LINK wristband can estimate the value of heart rate in beats per minutes (BPM) using photoplethysmography.[2] However, it does not give access to raw heart rate data, limiting the ability to compute heart rate variability. At first, the wristband estimates user's heart rate; once it is done, it will record the wearer's BPM every second. At the core of our different studies, we want to explore the potential of off-the-shelf devices in providing new interaction schemes in VR. Thus, we decided to use a wearable heart rate monitor as it has been demonstrated to be accurate enough for entertainment and sports applications; it can also be easily integrated in VR experiences (Wang et al. 2017; Gaskin et al. 2017; Houzangbe et al. 2018b).

The application consists of a simple screen that shows all the information needed by the participants (see Fig. 1):

- On the bottom left corner, the instructions they have to follow (e.g., "increase your heart rate," "lower your heart rate," etc.).
- In the center, a plot of their heart rate (BPM) in real time and the different level of heart rate they have to reach.
- On the bottom, the current heart rate value.

[2] A simple and low-cost optical technique that can be used to detect blood volume changes in the microvascular bed of tissue.

3.2 Experimental procedure

First, the participants are asked to read and sign a participation consent form and another form certifying in particular that they have no heart problems and that they accept their physiological data to be monitored and used in a series of experiments. They then proceed to fill a pre-experimentation questionnaire, to record demographic data. We then explain to the participants the different phases of the experiment and their respective goals. We also instruct the participants that they are allowed to use whichever technique they want to influence their heart rate. We do not suggest any strategies to the participants, they develop them by themselves (breathing, walk-in-place, sitting and more). Finally, we answer any questions they might have. We then equip the participants with the Mio LINK and an audio headset and launch the application.

The application is split in three parts. The first is a blank screen informing the participants that the calibration of their heart rate baseline is being performed. To determine the user's baseline heart rate, we based our protocol on the works of Nogueira et al. (2016) and Dekker and Champion (2007). The application records 150 values of BPM, while the participants listen to the music "Union's Weightless." Values are recorded every second, the estimated duration of the calibration is 2 min and 30 s. The participants stay standing during that time. A mean value of those 150 recordings is then computed to determine the participant's baseline heart rate.

Once the calibration is over, the application switches to the second screen, showing on the top left corner different breathing patterns that the participants have to follow (a fast and shallow breathing pattern and a slow and deep breathing pattern, see Fig. 1a). The patterns are represented by an animated lungs icon that grows and shrinks in rhythm. The goal of this part is to allow the participants to observe the effects of these breathing patterns on their heart rate. This phase is inspired by the work of Sroufe (1971) and lasts 2 min.

After this learning phase, the experiment begins. It consists in a series of 8 exercises where the participants have to either increase their heart rate or lower it, based on the work of Manuck et al. (1975) (see Fig. 1b, c). Each exercise lasts 1 min and 30 s. There is a resting period of 45 s between each exercise. The participants are told this phase allows them to go back to a heart rate value close to their baseline. We considered that the participants that reached a HR between their baseline and their baseline+10BPM successfully reset their HR. This period proved to be effective, as 75% (43/58) of the participants succeeded in reaching a HR close to their baseline during 4 or more of the 7 resting phases.

The succession of exercises is randomized. However, during the experiment the same type of exercise (increase heart rate or lower heart rate) can only happen successively once. During an exercise, the participants have to maintain their heart rate in the designated zone as long as possible. The zones are represented on screen by green areas in which the heart rate must be.

We conducted a series of pretest with different members of our team in order to define the different values for heart rate control. These pretests consisted in having multiple persons doing the experiment two times to evaluate which values they could and could not reach in order to determine what level of challenge was acceptable. With each exercise the difficulty is increased. This is done to evaluate the level of ability in heart rate control each participant can reach.

- For the acceleration of heart rate, the goals to reach are as follows (or higher):

  1. baseline value + 20 BPM;
  2. baseline value + 25 BPM;
  3. baseline value + 30 BPM;
  4. baseline value + 35 BPM.

- For the reduction of heart rate, the goals to reach are as follows (or lower):

  1. baseline value + 5 BPM;
  2. baseline value;
  3. baseline value − 5 BP;
  4. baseline value − 10 BPM.

After our pretest results, we decided to put the first reduction value lightly over the baseline value, and this was done to compensate for the potential stress inducing process inherent to the nature of an experimental environment.

3.3 Measures

Prior to the experiment, the participants answer a short profile questionnaire, asking them about their age, sex, level of physical condition and how often they exercise. After the experiment, we ask them how much they felt capable

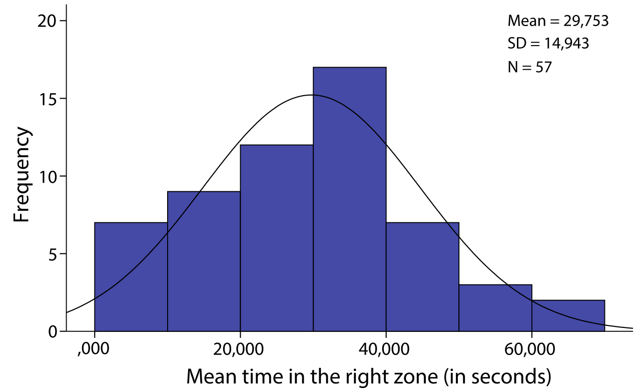


Fig. 2 The distribution of participants mean time in the designated zone during the experiment

of controlling their own heart rate, its acceleration and deceleration.

To evaluate the participants competency in controlling their heart rate, this one is registered during the experiment as well as the amount of time they spend in the designated zone during each exercise.

We recruited 58 participants for this experiment (14 women and 44 men) aged between 21 and 44 years old ($M = 25.58$, $SD = 5.628$). We had to remove one participant from our panel due to a technical issue during the experiment.

3.4 Results

To measure how well the participants succeeded in the different conditions, we calculated the mean time they spent in the designated heart rate zone for each round of the trials. The Shapiro-Wilk test, on the mean time in the designated zone, does not validate the non-normality of the distribution (Shapiro–Wilk's $p = .207$, see Fig. 2). From a qualitative standpoint, we observe that the distribution seems to follow a normal distribution with an asymmetry to the left. We found no statistical correlation between the recorded heart rate baseline and the capacity to self-regulate heart rate, using the Spearman correlation test ($p = .474$, $r = .097$). We also do not observe statistical correlation between the participants' reported level of physical condition and their success in maintaining their heart rate in the right zone, using the Spearman correlation test ($p = .051$, $r = .260$). While it is only nearly not significant the correlation coefficient is weak so that we cannot conclude to any correlation between the two.

We then computed the different quartiles for the mean time in the designated zone for exercises 1 and 2 for the "increase heart rate" and for the "reduce heart rate," to estimate an acceptable time frame and start the classification of our participants. The different intervals defined by the quartiles are for the "increase heart rate": [0; 19[s, [19; 37[s, [37; 62[s and [62–90] s. And for "reduce heart rate": [0; 19[s, [19; 32[s, [32; 48[s and [48; 90] s.

Based on those time values, we reduced our panel by considering the 36 participants that were able to reach at least half the time of the first quartile (10 s of heart rate control) to calculate the new quartiles. We thus recalculated the intervals and ended up with [12.5; 29[s, [29; 48[s, [48; 65.5[s and [65.5; 90] s for the "increase heart rate" trial. And for the "reduce heart rate" trial, the boundaries are: [12.5; 28[s, [28; 36[s, [36; 50[s and [50; 90] s. These intervals allow us to classify the participants in categories ranging from 0 (unable) to 4 (strong) for each trial type and compute a mean value of those scores to have a definite result on their ability for the 57 initial participants:

- 21 didn't succeed in controlling their heart rate (9 didn't succeed in accelerating their heart rate and 11 didn't succeed in reducing their heart rate and 1 didn't succeed in either).
- 2 are considered weak at controlling their heart rate.
- 13 are considered regular at controlling their heart rate.
- 13 are considered good at controlling their heart rate.
- 8 are considered exceptional at controlling their heart rate.

4 Study 2: Voluntary heart rate control in a virtual reality experience

4.1 System

Following a similar pattern than the first study described in this paper, we developed an immersive virtual reality game that will use the participants heart rate as a game mechanic. The game consists in a series of 8 heart rate control exercises, one for each level in the game.

4.1.1 Apparatus

We used a HTC Vive VR System, a desktop PC (composed of an Intel Core I7-6700HQ @ 2.60 GHz processor and a Nvidia Geforce GTX 1080 graphics card) and headphones for this experiment. Following our previous study, we used a Mio LINK heart rate wristband to record heart rate values. The navigation space was set up to be 3×3 square meters.

4.1.2 Influence of the physiological data

The participants unlock the end of each level by reaching certain heart rate values during a defined time. From the results of the first study presented in this paper, we chose the heart rate thresholds to be: (1) reaching the baseline value and lower, when reducing one's own heart rate and (2) reaching the baseline value plus 20 BPM and higher, when increasing one's own heart rate.

To give feedback to the participants on their heart rate, each room has a specific mechanism that is linked to it. The different interactions are described in the next section. To induce a sense of agency, we wanted to tie the effect of heart rate to a "logical" consequence in the virtual environment (e.g., the higher the heart rate the bigger the fire, the lower the heart rate the lower the volume of gas, etc.). Indeed, it has been demonstrated by Groenegress et al. (2010) that anchoring physiological data in VR can enhance the relationship between the user and the VR environment. This can be linked with the principle of consistency presented by Jeunet et al. (2018).

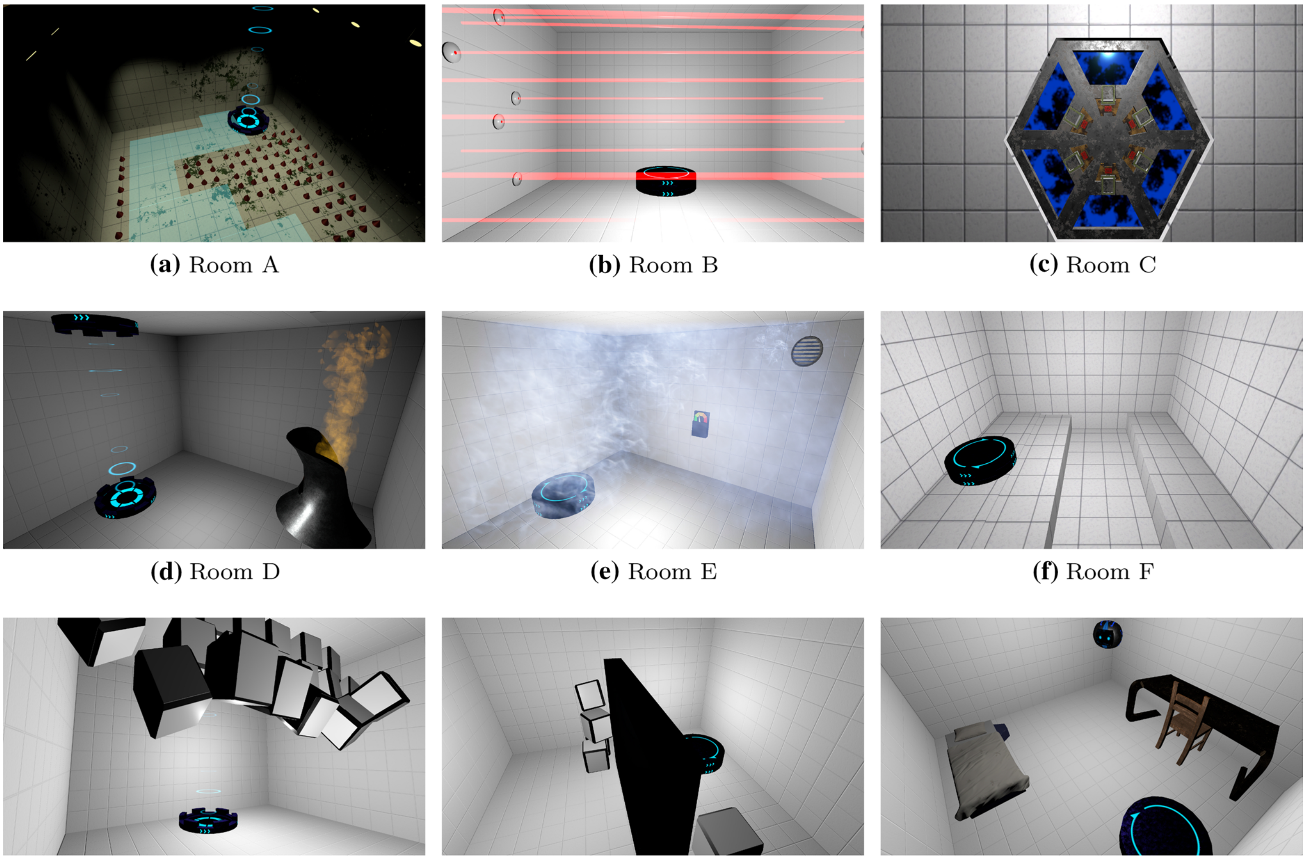
4.1.3 VR game

We developed a game partly inspired by *Portal*.[3] Placed in a futuristic experimental laboratory, the game consists of a succession of rooms that each possesses its unique mechanics and interaction. The game starts in a furnished room with a floating drone in a corner. In order for our biofeedback game mechanic to be adapted to each participant, we start every experiment with a calibration phase, the same one presented in the first study of this paper. The calibration takes place in the starting room (see Fig. 3i), in the VR environment, during that time the participants can explore the room but are invited not to be too active in order to not raise their heart rate unnecessarily. The participants can navigate naturally in the virtual environment. Once the calibration is over, the drone explains the context and gives the instructions to the participants.

The participants change room by walking to a teleporter that activates once the room's task is complete. Between each room, they wait in an empty elevator-like room with music. The different rooms present in the game are:

- *Room Acc. A* (see Fig. 3a): the room is plunged in darkness and spikes litter the floor. Spotlights on the walls progressively illuminate to show a safe passage to the teleporter. The spotlights will progressively start lighting when the heart rate is over the threshold.
- *Room Dec. B* (see Fig. 3b): the room is filled with lasers that block the passage to the teleporter. The lasers turn partially transparent when the heart rate is under the threshold.
- *Room Dec. C* (see Fig. 3c): the room is separated in half by a door and the player is equipped with a gun. Once the teleporter is active, the gun activates, and the par-

[3] Valve Corporation—2007.



(**a**) Room A (**b**) Room B (**c**) Room C
(**d**) Room D (**e**) Room E (**f**) Room F
(**g**) Room G (**h**) Room H (**i**) Starting room

Fig. 3 Screenshots of the different rooms in the VR game of the second study

ticipant can shoot at the door until it opens. The gun is inactive until the heart rate has been under the threshold for enough time.

- *Room Acc. D* (see Fig. 3d): there is a brazier in the room, that will get bigger until the teleporter is active. The fire grows as long as the heart rate is over the threshold.
- *Room Dec. E* (see Fig. 3e): the room is filled with gas, once the gas is cleared the teleporter activates. The amount of gas diminishes while the heart rate is under the threshold.
- *Room Acc. F* (see Fig. 3f): there is an electrified floor that separates the player from the teleporter in the room, a bridge will progressively move to allow the participants to reach the other side of the room. While the heart rate is over the threshold, the bridge moves toward the starting platform until connecting both sides.
- *Room Dec. G* (see Fig. 3g): the room is separated in half by a pile of cubes that cannot be displaced. Once the teleporter is activated, gravity is turned off and the cubes start floating, freeing the passage to the other side. The gravity is set off once the heart rate has been under the threshold for a sufficient amount of time.
- *Room Acc. H* (see Fig. 3h): the room is separated in half by a wall. Once the teleporter is activated the wall shatters, allowing passage to the other side. The wall shatters once the heart rate has been over the threshold for a sufficient amount of time.

At the beginning of each room, the specific instruction is issued to the participant: "To complete this room: raise your heart rate" or "To complete this room: lower your heart rate." During each trial, the participant is shown his/her current heart rate on screen and the goal he/she has to reach. Once they are in the designated heart rate zone, the mechanism of the different rooms progressively activates. The participants have to be in the designated zone for a defined amount of time (see Sect. 4.3) in order to fully activate the mechanisms and the teleporter to complete the trial. They have a maximum of 1 minute and 30 s to complete each room. If they fail to finish in time, they are automatically teleported to the transition room (elevator); this is done to have the participants experience the game fully.

The order of the rooms is randomized at launch. After they complete the 8 different rooms, the participants are teleported back to the starting room and the game ends.

4.2 Participants

From the 57 participants of the previous experiment, we selected 30 persons to participate in the second part (see Sect. 3.4), 8 women and 22 men, aged between 21 and 43 years old ($M = 25.87$, SD = 5.237). We selected this panel based on the availability of the participants and their level of competency. From the classification of the previous study: 8 participants did not succeed the heart rate control (5 that failed to reduce their heart rate and 3 that failed to accelerate their heart rate), 8 are regular at controlling their heart rate, 8 are good at controlling their heart rate, and 6 are exceptional at controlling their heart rate. To perform our analysis, we parted the participants in two main groups: the "low control" group (LCG), consists of the 8 participants that didn't succeed and the 8 participants that are regular at controlling their heart rate, and the "high control" group (HCG), consists of the 8 participants that are good at controlling their heart rate and the 6 that are considered exceptional at controlling their heart rate (see the "Appendix" for detailed distribution).

Our panel was generally well experienced in VR, on the question "How experienced are you with virtual reality? (1 ="No experience," 5 = "It's my working tool")", the mean score was 4.63 (SD = .669). We purposefully chose VR experienced participants in order to avoid them being more focused on discovering the technology rather than fully experiencing the game.

4.3 Variables and measures

The competency is central to our study; thus, we developed two versions of the game with different difficulties, each participant tests both versions of the game. The difficulty and the competency are used as independent variables:

- Difficulty:
  - Low difficulty (LD): the participant has to hold his/her heart rate in the designated zone for 10 s (cumulative) in each room.
  - High difficulty (HD): the participant has to hold his/her heart rate in the designated zone for 20 s (cumulative) in each room.
- Competency group:
  - Low Control Group (LCG): participants that have low to no control on their heart rate.
  - High Control Group (HCG): participants that have good to exceptional control on their heart rate.

Based on the results of the first study, we decided that affecting the control timeframes was an appropriate difficulty mechanic. Moreover, we already have available time frames, thanks to the results of the first study. The LCG is composed of participants that did not succeed in maintaining the 10 s frame and participants that are considered not highly competent in heart rate control. Thus, we chose the time frames to allow the participants to somewhat succeed in the first difficulty (to limit frustration and the inability to complete the task) but struggle in the second one (for the LCG).

To obtain the participants' feedback on the experience, we built a questionnaire based on multiple relevant questionnaires present in the literature. For user engagement, we studied the *Presence Questionnaire* (Witmer and Singer 1998), the *User Engagement Scale (UES)* (Wiebe et al. 2014) as well as the *Game User Experience Satisfaction Scale (GUESS)* (Phan et al. 2016) and selected the sub-metrics relevant to our study: perceived usability, felt involvement, personal gratification and focused attention. Regarding the agency part of our questionnaire, we studied the work of Argelaguet et al. (2016) and Gorisse et al. (2017) and reformulated the questions in order to be focused on the heart rate mechanic. All our questions are based on 5 points differential semantic scales (see Table 1).

We recorded objective variables (the combined duration of completion of the trials, the number of rooms failed) and qualitative data based on the participants' post-experience feedback (questionnaire and semi-structured interviews).

Participants experienced both difficulties of the game, in the same order. Firstly, the low difficulty (LD) then the high difficulty (HD). The difficulty levels are built to provide particular levels of challenge. The LD is accessible to both groups of participants, while the HD naturally poses a strong challenge to the LCG. Engagement and agency in interactive experiences are conditioned by reaching and maintaining a relative state of flow (balance between difficulty and competency). A lack of balance can create frustration and worsen user experience. Heart rate control is a complicated game mechanic to master. The lack of control over a game mechanic can lead to a high level of frustration and disinterest with an experience. By not counterbalancing our conditions, it is possible for the participants to experience a progressive increase in difficulty. This creates a learning curve that allows our experience to propose a challenge balancing difficulty and competency (flow). With this, we can limit the effect of frustration and somewhat ensure our participants experience the game and its mechanics to their full extent.

Table 1 Questionnaire with 5 dimensions: Perceived Usability (PU), Felt Involvement (FI), Personal Gratification (PG), Focused Attention (FA) and Agency (AG)

ID	Question
PU1	How confusing to use were the game mechanics?[a] (UES)
PU2	How responsive was the environment to the actions that you initiated (or performed)? (UES)
PU3	How demanding was the experience?[a] (UES)
PU4	How much could you do the tasks needed during the game? (UES)
PU5	How much did you feel frustrated during the game?[a] (UES)
PU6	How mentally taxing were the game mechanics?[a] (UES)
FI1	How fun was the gaming experience? (UES)
FI2	How drawn were you into the gaming tasks? (UES)
FI3	How completely were all of your senses engaged? (PQ)
FI4	How involved were you in the virtual environment experience? (PQ)
PG1	How confident were you about your success in game? (GUESS)
PG2	How successful did you feel when you overcame the obstacles in the game? (GUESS)
PG3	How much did you want to do as well as possible during the game? (GUESS)
PG4	How focused were you on your own performance while playing the game? (GUESS)
PG5	How much did you feel that the game constantly motivated you to proceed further to the next level? (GUESS)
PG6	How much did you find that your skills were gradually improving through the course of overcoming the challenges in the game? (GUESS)
FA1	How much did you lose track of the world around you? (UES)
FA2	How much involved were you in the game that you lost track of time? (UES)
FA3	How much could you block most other distractions when playing the game? (GUESS)
AG1	How much did you feel like you were able to interact with the environment the way you wanted?
AG2	How much did you find the heart rate control task difficult to perform?[a]
AG3	How much did you feel like your heart rate control allowed you to influence the game mechanics?

[a]Results to the questions are reversed (the higher the score the better the value)

4.4 Experimental procedure

The participants start by answering a short profile questionnaire, asking about their VR experience, sensitivity to cybersickness and gaming habits. We then explain to them that they are going to do an experience based on similar principles as the first experiment in which they participated, except this time in VR. We explain to them the different parts of the experience (without detailing the different rooms) and how they are supposed to complete the game. The participants are not told in which group they belong (LCG or HCG), to not influence their results in game. We answer the questions the participants have regarding the experiment if something is amiss. We then proceed to equip the participants with the wristband and the VR headset.

Once they complete the LD condition, the participants answer the post-experiment questionnaire and gear up again to do the HD condition. They then answer the questionnaire a second time, and we conduce a short semi-structured interview to gather information about their personal motivation during the VR experience compared to their motivation during the first non-VR experience, their preferred condition (LD vs HD) and how they felt about the game difficulty.

4.5 Hypotheses

- H1: The usage of a direct heart rate biofeedback is an engaging game mechanic.
- H2: User engagement (measured through perceived usability, felt involvement, personal gratification and focused attention) is positively proportionally linked to the voluntary heart rate control level of competency.
- H3: The use of the direct heart rate biofeedback induces a high sense of agency, tied with the level of competency.

4.6 Results

We analyze our results considering two different angles, a between-subjects design, comparing the results of the competency groups (LCG vs. HCG, independent measures), and a within-subjects design, comparing the results between the two levels of difficulty (LD vs. HD, repeated measures) of the game. To evaluate the interaction between the competency and difficulty on the questionnaire's answers, we use a mix between-within ANOVA (Competency * Difficulty), even if our measures are not following a normal distribution. However, we

Table 2 Perceived usability scores

Grp	Rnd	PU3			PU4			PU6		
		n	*M*	SD	*n*	*M*	SD	*n*	*M*	SD
LCG	LD	16	3.44	.96	16	4.38	.72	16	4.13	1.26
	HD	16	2.94	.93	16	3.88	.89	16	3.56	1.09
HCG	LD	14	3.50	.86	14	4.50	.52	14	4.79	.58
	HD	14	2.71	.73	14	4.07	1.14	14	4.64	.63
Total	LD	30	3.47	.90	30	4.43	.63	30	4.43	1.04
	HD	30	2.83	.83	30	3.97	1.00	30	4.07	1.05

Table 3 Felt involvement scores

Grp	Rnd	FI1			FI2			FI3			FI4		
		n	*M*	SD	*n*	*M*	SD	*n*	*M*	SD	*n*	*M*	SD
LCG	LD	16	3.81	.981	16	4.12	1.147	16	3.25	1.183	16	3.75	1.065
	HD	16	3.44	1.153	16	4.00	.966	16	3.44	1.031	16	4.13	.885
HCG	LD	14	3.43	.756	14	4.00	.877	14	3.36	1.008	14	4.07	.730
	HD	14	3.86	.864	14	4.14	1.167	14	3.50	1.019	14	4.07	.829
Total	LD	30	3.63	.890	30	4.07	1.015	30	3.30	1.088	30	3.90	.923
	HD	30	3.63	1.033	30	4.07	1.048	30	3.47	1.008	30	4.10	.845

base this decision on the work of Winer (1962) regarding the robustness of ANOVA against type 1 errors. We then use post hoc Mann–Whitney tests for the between-subjects' comparisons or post hoc Wilcoxon signed ranks tests for the within-subjects' comparisons when the ANOVA shows an interaction between both factors (Competency * Difficulty).

4.6.1 Perceived usability

The results of our mixed between-within analysis of variance show that there is no significant interaction between the difficulty and the competency of the participants for neither of the questions. For PU1, PU2 and PU5, there are no significant influence of the difficulty nor the competency on those questions. There is a substantial effect of difficulty for questions PU3 (Wilk's Lambda = .644, $F(1, 28) = 15.458$, $p = .001$, partial eta squared = .356). Despite low p values, a false discovery rate test demonstrates that there are no significant effects of difficulty for questions PU4 (Wilk's Lambda = .853, $F(1, 28) = 4.816$, $p = .037$, partial eta squared = .147) and PU6 (Wilk's Lambda = .841, $F(1, 28) = 5.293$, $p = .029$, partial eta squared = .159). The results, presented in Table 2, indicate a better perceived usability for low difficulty over the high difficulty. Even if the p value is low, a false discovery rate test shows that there is no significant effect of the competency of the participants on the scores of question PU6 ($p = .01$, partial eta squared = .215).

4.6.2 Felt involvement

The results of our mixed between-within analysis of variance show that there is a significant interaction between the difficulty and the competency of the participants (Competency * Difficulty) only for question FI1 (Wilk's Lambda = .759, $F(1, 28) = 8.894$, $p = .006$, partial eta squared = .241). There are no significant interactions for the questions FI2, FI3 and FI4, and neither is there any significant influence of the difficulty nor the competency on these three items.

We first analyze the results depending on the competency group for FI1, with a Bonferroni correction applied ($p < .0125$). When looking in detail, we find no significant differences between the difficulty levels for the LCG. The HCG does not report significantly different scores depending on the difficulty but only a slight tendency ($p = .014$, $Z = -2.449$). We can note that the score is higher for the high difficulty (M(HCG-HD) = 3.86, SD = .864) than for the low difficulty (M(HCG-LD) = 3.43, SD = .756). The full results are reported in Table 3.

While we can not conclude how directly felt involvement is impacted, we observe for the high difficulty (HD) a tendency for an overall better reported felt involvement for the HCG. The LCG reports diverse responses, some favoring the low difficulty (FI1) and some the second one (FI4). We cannot conclude how strongly the control affects the involvement for all the participants; however, we can observe a slight tendency for higher involvement for the HCG during the high difficulty compared to the first one.

Table 4 Personal gratification scores

Grp	Rnd	PG2			PG5			PG6		
		n	*M*	SD	*n*	*M*	SD	*n*	*M*	SD
LCG	LD	16	3.31	1.35	16	3.56	1.153	16	3.31	1.14
	HD	16	3.94	1.06	16	3.56	.964	16	3.50	1.16
HCG	LD	14	4.00	.88	14	3.36	.842	14	3.29	.91
	HD	14	4.29	.73	14	3.71	.726	14	3.71	1.14
Total	LD	30	3.63	1.19	30	3.47	1.008	30	3.30	1.02
	HD	30	4.10	.92	30	3.63	.850	30	3.60	1.13

We also performed a series of *T* tests to measure if the scores on involvement were significantly higher than the neutral value (3). The results show that the felt involvement was significantly higher ($p < .001$) for questions FI1, FI2 and FI4 in the LD condition and significantly higher for questions FI1 ($p = .002$), FI2 ($p < .001$), FI3 ($p = .017$) and FI4 ($p < .001$) in the HD condition. Suggesting that the experience was highly involving.

The fact that the participants experience the same experience twice with only a difficulty change might explain these results. Indeed, some participants report in the post-experiment interview that they prefer the high difficulty, one participant in the LCG reporting that "[he/she] could better enjoy the environment and the game, it was more challenging and [he/she] felt more involved." On the contrary, another participant reports that "[he/she] preferred the low difficulty, because it was more about discovering the environment and that the second one was less involving."

4.6.3 Personal gratification

The results of our mixed between-within analysis of variance show that there is no significant interaction between the difficulty and the competency of the participants (Competency*Difficulty) for neither of our questions regarding personal gratification. Questions PG1, PG3, PG4 and PG5 return no significant influence of the difficulty and the competency. Moreover, questions PG2 and PG6 show no significant influence of the competency.

Despite low *p* values, a false discovery rate test demonstrates that there is no significant influence of the difficulty over the scores for PG2 (Wilk's Lambda = .862, $F(1, 28) = 4.491$, $p = .043$, partial eta squared = .138) and PG6 (Wilk's Lambda = .830, $F(1, 28) = 5.723$, $p = .024$, partial eta squared = .170). Looking at the results in Table 4, we note that the participants seem to feel more rewarded during the high difficulty, as it "felt more challenging, the difficulty was more satisfying." However, the lack of significant differences do not allow us to formulate strong conclusions.

Surprisingly, we do not observe higher personal gratification from the LCG in the LD condition, some participants even reporting that the difficulty was too easy in this condition and it did not feel as rewarding as the second one.

We also performed a series of *T* tests to measure if the scores on personal gratification were significantly higher than the neutral value (3). The results show that the reported gratification was significantly higher than the neutral for questions PG1 ($p = .001$), PG2 ($p = .007$), PG3 ($p < .001$), PG4 ($p < .001$) and PG5 ($p = .017$) in the LD condition and significantly higher than the neutral for PG1 ($p = .001$), PG2 ($p < .001$), PG3 ($p < .001$), PG4 ($p < .001$), PG5 ($p < .01$) and PG6 ($p = .007$) in the HD condition. This indicates that the experience was highly gratifying for our participants.

4.6.4 Focused attention

Despite a low *p* value, a false discovery rate test shows that the results of our mixed between-within analysis of variance show no significant interaction (Competency * Difficulty) for question FA3 (Wilk's Lambda = .824, $F(1, 28) = 5.996$, $p = .021$, partial eta squared = .176). Questions FA1 and FA2 return no significant interactions between the two factors.

The analysis of variance showed that there is a significantly large influence of the difficulty for question FA1 (Wilk's Lambda = .761, $F(1, 28) = 8.794$, $p = .006$, partial eta squared = .239). We can observe that the participants are less focused during the low difficulty ($n = 30$, M(all-LD) = 2.60, SD = 1.329) than the high difficulty ($n = 30$, M(all-HD) = 3.30, SD = 1.317).

This points toward the fact that the participants need to be more focused during the HD condition of the game, as it is more demanding to control their heart rate, joining the results of the previous sections, the difficulty being more rewarding and the game harder to master.

4.6.5 Agency

The results of our mixed between-within analysis of variance show no significant interactions (Competency * Difficulty) for neither of our questions regarding agency. Moreover, question AG3 returns no significant effect for neither the difficulty nor the competency. We observe a tendency for the

Table 5 Agency scores

Grp	Rnd	AG1			AG2			AG3		
		n	*M*	SD	*n*	*M*	SD	*n*	*M*	SD
LCG	LD	16	2.88	1.147	16	3.75	1.065	16	3.94	1.063
	HD	16	2.62	1.088	16	2.94	.929	16	3.81	.981
HCG	LD	14	3.29	.994	14	3.93	.829	14	3.79	1.188
	HD	14	3.43	.852	14	3.36	1.151	14	4.29	.469
Total	LD	30	3.07	1.081	30	3.83	.950	30	3.87	1.106
	HD	30	3.00	1.050	30	3.13	1.042	30	4.03	.809

influence of the competency on AG1 ($p = .079$, partial eta squared = .106), the HCG reporting better sense of agency.

We also note a significant influence of the difficulty for question AG2 (Wilk's Lambda = .754, $F(1, 28) = 9.128$, $p = .005$, partial eta squared = .246), the participants reporting higher scores for the low difficulty ($n = 30$, *M*(all-LD) = 3.83, SD = .950) compared to the high difficulty ($n = 30$, *M*(all-HD) = 3.13, SD = 1.042). The participants in the LCG do not report a significantly a lower sense of agency during the HD for the question AG2 but only a slight tendency, after a Bonferroni correction ($p = .027$, $Z = -2.216$, *M*(LCG-LD) = 3.75, *M*(LCG-HD) = 2.94). The full results are displayed in Table 5.

Overall, we observe that the HCG participants report a seemingly higher sense of agency compared to the LCG participants; this is especially observable in the HD condition. Despite reporting a higher level of difficulty during the HD condition compared to the LD condition, the HCG feel a stronger sense of agency during the high difficulty, as it is more in accordance to their capabilities. On the other hand, the participants in the LCG seem to report a better sense of agency during the low difficulty.

We also performed a series of *T* tests to measure if the scores on reported agency were significantly higher than the neutral value (3). The results show that the reported sense of agency was significantly higher than the neutral for questions AG3 ($p < .001$) in both difficulties (LD and HD). This tends to demonstrate that the participants felt a strong sense of agency during our experiment, using only their heart rate as a control paradigm.

4.6.6 Objective results

The results of our mixed between-within analysis of variance show no significant interaction (Competency * Difficulty) for the number of failed trials nor for the combined tasks time. Regarding the objective data, we expected the participants in the LCG to perform significantly lower than the participants in the HCG, by failing more trials. However, we find no significant differences neither between the two competency groups (LCG and HCG) nor between the two levels of difficulty (LD and HD). It is interesting to note that most of the participants succeeded in both difficulties despite not being predicted to do so. Indeed, the mean number of rooms failed was 0.73 during the low difficulty (*M*(LCG-LD) = .75, *M*(HCG-LD) = .714) and 0.97 in the second one (*M*(LCG-HD) = .8125, *M*(HCG-HD) = 1.14). In each of the difficulties, 16 of our 30 participants succeeded every trial in the game (8 participants from each group for each difficulty). Regarding the average time necessary to finish all the rooms, the participants in the HCG scores are lower for the low difficulty (356 s for the HCG vs 383 s for the LCG). However, this result is different for the high difficulty where the participants register almost the same mean times (447 s for the LCG vs 448 s for the HCG).

4.7 Discussion

While biofeedback has been studied in multiple contexts, whether it be exergames (Ketcheson et al. 2015), video games (da Silva et al. 2014) or self-efficacy (Weerdmeester et al. 2017), very few studies have been conducted looking at the effects of voluntary biofeedback control on user experience in VR. This experiment was designed to study how a voluntary control of heart rate could affect user engagement and the sense of agency in VR.

To study the effects on user engagement, we measured different factors in order to determine how they were impacted by this new mechanic. To measure if the biofeedback mechanic can be engaging, we decided to oppose different competency groups and also evaluate their direct feelings toward the experience.

We hypothesized that the usage of a direct heart rate biofeedback could be an engaging game mechanic (H1). The participants reported a significantly higher level of involvement and personal gratification, compared to the neutral value, for both difficulties of the experiment. Indeed, this seems to indicate that the participants felt strongly engaged during the experience. While it could be imputed to the VR medium, it is important to note that the participants are all highly experienced in VR. Moreover, the only game mechanic present in the game was centered around the control of heart rate, so the felt involvement, gratification and focused attention are all consequences of this factor only.

These results tend to validate our hypothesis H1 and are in accordance with previous studies (Nacke et al. 2011; Houzangbe et al. 2018a).

From our results, we cannot straightly confirm that the participants with the more control are more engaged in the experience whatever the difficulty level is (H2). However, we can observe a tendency in higher overall engagement for the HCG, through higher results in the different factors. Moreover, it is interesting to note that the competent participants report higher levels of engagement when the difficulty is higher. This can be linked to the concept of flow (Csikszentmihalyi 1975), which states that when the challenge related to the task fits one's level of competency then one's level of engagement will grow significantly.

We predicted that the use of voluntary heart rate control as a game mechanic in VR could lead to a high sense of agency and that it was tied with competency (H3). The results of our experience tend to confirm that hypothesis. Firstly, we can note that the participants reported a significantly higher sense of agency compared to the neutral value, demonstrating that they felt a high level of agency only using their heart rate to interact with the different elements of the game. Moreover, we observe higher reported levels of agency from the participants in the HCG compared to the participants in the LCG. Those results are also observable when comparing the reported agency between the two difficulties for each group. While the participants in the LCG tend to report a higher sense of agency during the low difficulty, the participants in the HCG report the opposite (see Table 5). Moreover, the participants in the HCG report fairly high level of sense of agency whichever the difficulty, meaning they felt that their will of action (accelerating their heart rate or lowering it) was translating as intended in the game. This is in accordance with the model proposed by Jeunet et al. (2018), by respecting the different principles one can experience the sense of agency. The participants in the LCG report, as expected, lower results for that factor; however, they score fairly high for the low difficulty. This emphasis the necessity to propose experiences that are adapted to the competency of each participant.

It is, however, important to mitigate such results, as the participants expressed how important was the contextualization of the heart rate control in a game and how it helped them to be more invested and succeed better. Indeed, most of our participants succeeded in the game and 25 out of the 30 confirmed that the use of VR and the contextualization of the interaction affected their level of motivation and helped them better respond to the challenge. Multiple participants reported that "the immersion provoked a clear augmentation of motivation," that the fact "it was a game [he/she] was more involved and motivated to succeed" and that "the experiment seemed easier in VR." This is in accordance to the work of Weerdmeester et al. (2017) and Prpa et al. (2018). These results can also relate to the conclusions of Wollmann et al. (2016) that games motivate players to engage and perform better in biofeedback training situations. This could also be linked to the conclusions of the work of Sroufe (1971), who denotes that the usage of feedback greatly accelerates the acquisition of direct heart rate control. However, the reported results on user engagement and agency are still coherent with our expectations.

While all the participants were exposed to heart rate control techniques with the breathing schemes in the first experiment, the freedom we offered them allowed for the development of different techniques and strategies for heart rate control. In the second experiment ,these translated well, as most of our participants fully succeeded in the game. This highlights the richness of biofeedback as a game mechanic that users are able to assimilate to personalize their immersive experience. If our choices may be discussed concerning effects of the lack of homogeneity of the techniques on our results, they can also be considered interesting as they represent a true use-case of VR.

5 Limitations

During the post-experiment interviews, most of the participants reported the fact that the experience was a VR game had strong effects on their motivation and success. This can be noted as a limitation to our work. This could have led to a change in involvement level and blurred the line between the classification we made thanks to the results of the pre-experiment. It could be interesting to have the pre-experiment done in a gamified VR environment and compare the results in heart rate control. This could lead to a redefinition of the intervals we previously considered and better the distinction of level of control between our participants. However, this could prove to be straining for the participants, as the pre-experiment lasted for a long time and having the participants fully equipped and immersed during a 30 minutes period might be uncomfortable.

The second part of our experiment taking place a few weeks after the first one, some of our participants were not available to conduct the VR experience. Limited by their availability, we built the groups in order to have a maximum of participants while still retaining a form of homogeneity on the distribution of competency. It would be interesting in a follow-up experiment to use a group of participants that directly follows our normal distribution of competency.

We can also highlight the possible learning effects of the protocol. Indeed, the participants experienced the same game twice, which could have helped them better learn and master the heart rate mechanic. As presented in our results and discussion, the participants reported different feelings about the repetition of the game. Some favoring their first playthrough while others favored the second one. This is a possible explanation of the results obtained for the HD condition, as participants were able to succeed, whichever group they were part of. However, if this might have affected the results more than anticipated, it was a integral part of our experimental design, proposing a progressive rise in challenge coupled with the learning effect allowing the participants to stay in a relative state of flow during the experience.

6 Conclusions

In this paper, we have presented a series of experiments designed to study the effect of a voluntary heart rate control mechanic on user engagement and the sense of agency in a VR experience. We hypothesized that this game mechanic could be highly engaging and provoke a high level of agency. We also hypothesized that user engagement and the sense of agency were tied with one's ability to control his/her heart rate.

We were able to directly translate the results of our first study, which consisted in quantifying acceptable levels of heart rate control and classifying participants in skill categories, into a VR experience. We demonstrated that the usage of direct voluntary heart rate biofeedback was able to bring a high level of engagement to our participants. We were also able to observe significant effects on the sense of agency in our participants using only heart rate as a game mechanic.

Discussing with the participants, most of them were positive about the series of experience they realized and some of them even felt the experiences helped them better understand how they could influence their heart rate.

While heart rate control might not be directly considered as a mean of interaction in VR, the interest of these results could reside in the impact of the usage of heart rate on the different parts of user experience. It has been demonstrated that VR exposure can affect the subjective experience, cognitive capabilities (Banakou et al. 2018) or behavior (Gorisse et al. 2019). Thus, modifying it through our own physiological data could have significant effects as well. Moreover, VR has been extensively used for exposure therapy (Bouchard et al. 2017) and clinical psychology (Bouchard and Rizzo 2019), demonstrating multiple benefits. Bouchard et al. (2012) concluded that the usage of biofeedback in immersive video games positively affected the reinforcement of stress management skills for soldiers. Thus, exploiting physiological data as direct sensory channels could better help people struggling with psycho-social adaptation problems or emotion regulation difficulties.

7 Future works

Even if the VR experiment generated high levels of engagement, it is interesting to note that some participants felt a bit frustrated with the lack of direct interactions. However, since we wanted to study the effects of voluntary heart rate control as a direct mechanic, we decided not to introduce extra game mechanics. It could be interesting to include in further studies more direct physical interactions. The combination of movement and heart rate control could be hard to balance, as movement could influence heart rate and the cognitive load might be a bit much for the users to bear at once. Furthermore, we decided not to oppose the usage of heart rate to a traditional interaction device (game controller). It would be interesting in a future study to have a correctly contextualized interaction that could be either done with heart rate or a controller and compare how it affects user experience. We would like to expand the panel of users, to better discriminate the participants' ability groups. Finally, we plan on proposing a counterbalanced VR experience that would help us measure the learning effect in order to better discriminate its impact on user experience.

8 Ethics statement

At the time of our study, we consulted with our institution, and it was considered that we did not need to validate that study through an ethical committee. Moreover, we followed the recommendations formulated by Madary and Metzinger (2016), especially the principles of non-maleficence and informed consent. The panel recruited for the proposed experiment consists of adult students from a virtual reality training curriculum and virtual reality professionals who volunteered to participate. The noninvasive devices integrated in our setup are regularly used by the subjects that we have solicited and are accessible to the general public. Moreover, our protocol preserves the anonymity of the subjects.

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Appendix

See Tables 6 and 7.

Table 6 Distribution of the participants selected for the second experiment depending on their results in the first experiment

ID	1	2	3	5	7	10	11	12
Accelerate score (1–4)	4	2	1	1	3	1	4	3
Reduce score (1–4)	3	1	2	4	3	4	2	1
Group	HCG (4)	LCG (2)	LCG (2)	HCG (3)	HCG (4)	LCG (2)	HCG (3)	LCG (2)
ID	16	17	21	22	24	26	46	47
Accelerate score (1–4)	1	2	4	1	2	3	2	4
Reduce score (1–4)	4	3	4	2	4	2	1	2
Group	LCG (2)	HCG (3)	HCG (4)	LCG (2)	HCG (3)	HCG (3)	LCG (2)	HCG (3)
ID	48	49	51	53	57	58		
Accelerate score (1–4)	2	4	3	3	3	2		
Reduce score (1–4)	3	4	4	3	2	2		
Group	HCG (3)	HCG (4)	HCG (4)	HCG (3)	HCG (3)	LCG (2)		

A mean value of both the acceleration and reduce scores (quatrile) is computed and then rounded depending on their performance

Table 7 Participants that failed in one or the other category and were selected for the second experiment; they are placed in the LCG

ID	4	6	9	13	14	19	20	54
Failed category	Reduce	Accelerate	Accelerate	Accelerate	Reduce	Reduce	Reduce	Reduce

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