Andreas Holzinger
Alan Pope
Hugo Plácido da Silva (Eds.)

LNCS 10057

Physiological Computing Systems

International Conferences
PhyCS 2016, Lisbon, Portugal, July 27–28, 2016
PhyCS 2017, Madrid, Spain, July 27–28, 2017
PhyCS 2018, Seville, Spain, September 19–21, 2018
Revised and Extended Selected Papers

Springer

Integrating Biocybernetic Adaptation in Virtual Reality Training Concentration and Calmness in Target Shooting

John E. Muñoz[1(✉)], Alan T. Pope[2], and Luis E. Velez[3]

[1] System Design and Engineering Department, University of Waterloo, Waterloo, Canada
john.munoz.hci@uwaterloo.ca

[2] NASA Langley Research Center, Hampton, USA
alan.t.pope@nasa.gov

[3] Department of Computer and Systems Sciences at Stockholm University, Stockholm, Sweden
levelezq@gmail.com

Abstract. Training military readiness can significantly reduce potentially avoidable mistakes in real life situations. Virtual Reality (VR) has been widely used to provide a controlled and immersive medium for training both trainees' physical and cognitive skills. Despite the tremendous advances in VR-based training for military personnel, the attention has been mainly paid on improving simulation's realism through hardware tools and enhancing graphics and data input paradigms, rather than augmenting the human-computer interaction. Biocybernetic adaptation is a technique from the physiological computing field that allows creating real-time modulations based on detected human states indicated by psychophysiological responses. Although very sophisticated, the creation of biocybernetic loops has been mainly confined to research laboratories and very complex and invasive setups. Moreover, the combination of VR applications and biocybernetic adaptation has rarely been pursued beyond exploratory experiments. The Biocyber Physical System (*BioPhyS*) for military training in VR constitutes the first fully integrated, distributed and replicable VR simulator that is biocybernetically modulated. *BioPhyS* uses neurophysiological and cardiovascular measurements recorded from wearable sensors to detect calmness and cognitive readiness states to create dynamic changes in a VR target shooting simulator. The design process, psychophysiological modeling, and biocybernetic loop technology integration are shown, describing a pilot study carried out with a group of non-military participants. We highlight the software elements used for the VR-biocybernetic integration, and the psychophysiological model created for the real-time system as well as the timeline used to develop the functional prototype. We conclude this paper with a set of guidelines for developing meaningful physiological adaptations in VR applications.

Keywords: Biocybernetic loop · Virtual reality · Military training · Virtual simulator · Target shooting · Neurophysiological · Cardiovascular · Cognitive readiness · Physiological adaptation · Psychophysiology

A. Holzinger et al. (Eds.): PhyCS 2016–2018, LNCS 10057, pp. 218–237, 2019.
https://doi.org/10.1007/978-3-030-27950-9_12

1 Background

Novel virtual reality (VR) technologies have been booming in the last five years, providing substantial evidence of the role that virtual simulations and immersive games will play in our modern society [1]. The widespread use of VR in education, health and training applications has been mainly driven by the need to improve particular user experience aspects such as *immersivity*, presence, and vividness through modern computationally generated graphics, visualization techniques and interactive sensors [2]. In this race to provide complementary technologies that will enhance the already realistic and highly engaging VR experiences, the physiological computing field has been illustrating how, via integrating human body signals into the virtual environments, users can extend the conventional human-computer communication pathways [3–5]. A more sophisticated way to use the physiological signals is by allowing the VR application to be aware of important users' psychophysiological states, such as stress or concentration levels, and to provide real-time adaptations accordingly. This physiological intelligence layer is known as the Biocybernetic Loop (BL) construct, and it employs adaptation strategies from control theory that places the human-in-the-loop to create more *humanized* systems [6]. In other words, BLs have the potential to augment VR applications by allowing the virtual elements to be modulated or paced by detected human states [7]. While research has been widely carried out in detecting human psychophysiological states through numerous computational techniques [8], it is the case that a lot less has been done towards using those states to intelligently and programmatically adapt the system [6, 9]. In response to this obvious and overlooked aspect in the marriage between VR and physiologically intelligent systems, we have conducted research that embraces both theoretical and practical notions and experiences for integrating biocybernetic adaptation in a VR simulator aimed at improving the self-regulation capabilities of military personnel. We document the process from the design to the implementation stages, and summarize our learnings in a set of guidelines that constitutes an effort towards disseminating biocybernetic technologies applied in VR simulations and games.

1.1 Military Training in VR and the *BioPhyS* Approach

The military sector has understood the importance of simulation and constant training for decades. Modern simulators nowadays have successfully integrated flexible, upgradeable, realistic and less expensive software and hardware elements that provide a very vivid representation of real-life scenarios for military training [10–12]. The capabilities of VR technologies to meet military applications were nicely summarized in human factors and man-machine systems meetings carried out in the US [11], featuring exciting projects covering applications for dismounted combatants, mission rehearsal for special operations, telerobotics, military training, and medical procedures. Examples of the use of VR simulators and applications can be found in all branches of the military industry: army, navy, air force and more [10]. Scientific validation of VR simulations used in clinical scenarios has been found in studies that employ very sophisticated technologies to provide exposure therapies for Post-Traumatic Stress Disorder patients [13]. The same approach, where very controlled, flexible and realistic simulations are used as rehabilitation and assessment tools, can be used for preventing avoidable mistakes in real-life scenarios with healthy participants by leveraging novel wearable, multimodal and cost-effective physiological sensing technologies, able to identify covert human states (e.g. stress, anxiety, mental workload) and react accordingly [14–16]. All in all, although the development of virtual simulators for military training has been widely explored, attention has been mostly paid to the machine side, trying to improve the realism and *immersivity* of the simulations, and little attention has been paid to system adaptation to users' needs and responses [10, 17].

Based on licensed patents from Pope and colleagues at NASA Langley [18–21], the Biocyber Physical System (*BioPhyS*) approach aims at creating an intelligent system that uses sophisticated biofeedback technologies to enhance cognitive skills in virtual military training. The *BioPhyS* system was initially conceived in the J&F Alliance Group (US Company) headquarters, in a close collaboration between physiological computing researchers, US veterans, VR developers and industry partners. The system integrates novel VR and biocybernetic technologies to deliver highly adaptive scenarios, aimed at boosting the training of critical cognitive skills in military personnel. The conceptualization of the *BioPhyS* system was the result of a brainstorming process carried out by the team wherein different potential applications and scenarios of biocybernetic systems were explored. After matching the company's clients and interests with the feasibility of using BLs as an adaptation mechanism, we came out with the idea of creating a virtual simulator for military training. In particular, we started exploring marksmanship training in target-shooting by developing a VR-based simulator. The *BioPhyS* approach has been designed for training two important human states: concentration and calmness, which have been found to be particularly relevant to promote cognitive readiness in shooting scenarios [16, 22]. By using both cardiovascular and neurophysiological measurements, calmness and concentration levels of trainees can be computed and used in real time to adapt the content in the VR target-shooting simulator dynamically. This paper shows the first effort carried out to deliver a functional and demonstrable prototype of the combined use of these technologies and it constitutes an initial step towards more complex and robust physiologically aware systems in the military industry.

1.2 The Biocybernetic Loop Engine Software Tool

To aid the integration process of BLs in the virtual target-shooting simulator, we used a previously developed engine that has been used to provide physiological intelligence in videogames[1]. The Biocybernetic Loop Engine (BL Engine) is an integrative software tool created to design, prototype, iterate and evaluate BLs in videogames and interactive applications made in Unity3D (Unity Technologies, San Francisco, USA) [23]. The BL Engine targets both users with and without expertise in game programming or physiological computing, since it can be fully operated through graphical user interfaces and it uses a streamlined method to integrate physiological parameters, adaptive rules, and game variables. The BL Engine includes signal acquisition, signal processing, and

[1] https://sites.google.com/view/physio2games.

feature extraction stages as well as a dedicated tool to create heuristic rules for the real-time adaptation (more details about the software design can be seen in [23]).

The BL Engine builds on top of past physiologically adaptive systems evaluated in games and virtual simulations [6, 24], as well as a robust theoretical framework in physiological computing systems [9, 25], and proposes a practical paradigm that can be used by both experts and technology enthusiasts. The BL Engine uses external clients to provide access to the sensors' services and make them available for further processing. The clients are developed in different programming languages such as C++, C#, and Java and they stream data from sensors through User Datagram Protocol (UDP) following the Reh@Net communication protocol [26]. For the *BioPhyS* approach, we used the cardiac panel that allows the communication with wearable and inexpensive chest strap sensors for heart rate such as the Polar (H7 and H10). Moreover, the concentration part of the system was designed to be measured by wearable brain-computer interface (BCI) devices supported in the BL Engine such as the Muse BCI[2].

2 Procedures and Tools

In this section, we describe our efforts towards designing and developing a physiologically adaptive system for target shooting using VR. There are three main stages: the virtual simulator design, the physiological characterization of the user's responses while interacting with the system and a final BL implementation in the virtual simulator.

2.1 *BioPhyS* Virtual Simulator

Why Use Biocybernetic Adaptation? After conceptualizing the *BioPhyS* system, we investigated the physiological responses associated with the desired human target state: concentrated and calm. Following marksmanship training guidelines [22], we learned that a crucial factor that has to be trained in overall marksmanship scenarios is shooting during the natural respiratory pause. Since the lack of oxygen might affect the performance of cognitive skills and reduce the visual acuity, training what is called *autogenic* breathing (autonomic self-regulation training [27]) aimed at relaxing the body and keeping a natural breathing pattern has been defined as a major component of firearms training [28]. Via providing proper brain oxygenation through an optimal respiration pace, peripheral responses such as heart rate (HR) and heart rate variability (HRV) will be controlled in an attempt to maintain both body and mind collected. Therefore, the BL construct seems to provide an ideal strategy for enhancing shooting performance by adapting the virtual elements that define the simulation difficulty to the users' concentration and relaxation levels (so-called calm, concentrated or cool, and collected state). To improve their scores in the shooting scenarios, users would have to use self-regulation strategies (e.g. respiration, sustained attention) that will keep them

[2] http://developer.choosemuse.com/tools/mac-tools/muselab.

calm and focused, thus increasing the likelihood of avoiding mistakes in real life scenarios [16].

Simulator Features and VR Implementation. An initial target-shooting scenario was developed for the *BioPhyS* approach, which simulates a training field with twenty horizontal tracks for the targets' positioning. Visually, the scenario includes conventional elements of an outdoor target shooting range such as cable reels, wooden tables, tents, barricades, weapons and water towers (see Fig. 1 left). Three weapons are used for training: The Pistols M1911 and SIG Sauer P250, and the Reichsrevolver M1879 (see Fig. 1 right), each with different impact strength on the targets.

A configuration console called Wizard of Oz (*Woz*) panel was implemented to allow trainers modify the simulation variables both before and during the interaction, providing a more controlled scenario for studying participants' responses and behavior once exposed to different stressors. The target-shooting simulator has a number of variables that were defined to carry out the physiological modulation. Variables were grouped considering their final effector as showed in Table 1:

Table 1. List of simulation variables carefully defined to create the physiological modulation in the BioPhyS simulator.

Simulation effect	Simulation variable	Range
Targets	Number of targets	3–20 (targets)
	Target Size	0.3–3 (units)
	Target Speed (horizontal)	0–5 (m/s)
	Target hardness	1–20 (units)
Simulation Environment	Day light	0–10 (units)
	Rain Intensity	0–1 (units)

The simulation can use both the wireless controllers and an air pistol gun adapted with the HTC Vive tracker to handle and shoot with the weapon. By using the wireless controllers, users can use the teleportation option to move freely in the virtual environment. The lateral buttons are used to grab the virtual gun, while the trigger is used for shooting (see Fig. 1, right).

2.2 Users' Physiological and Behavioral Characterization

After implementing an initial version of the system with the *Woz* panel and data logging, we carried out a first characterization study to better understand the cardiovascular and neurophysiological responses during different setups of the VR target-shooting training. For that, we used a repeated measures design in order to quantify the responses of users to different scenarios and difficulties.

System Setup. To provide a more immersive experience, we used the room-scale tracking system of the HTC Vive pro VR headset. Users can freely walk in an area of up to 12 m^2 (max 5 m between both tracking cameras), and the wireless HTC Vive controllers are used to provide manual interaction inside the virtual environment.

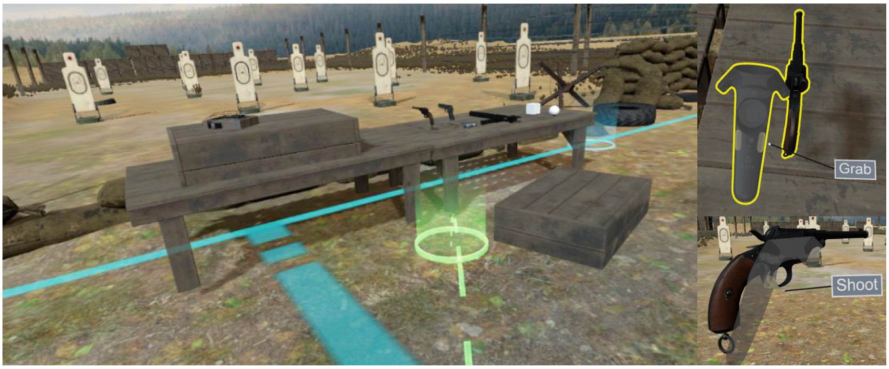

Fig. 1. Screenshots of the BioPhyS virtual simulator created in VR. Left: the shooting field with the targets placed randomly and a table with the guns. Right: the instructions for grabbing and shooting the Reichsrevolver gun.

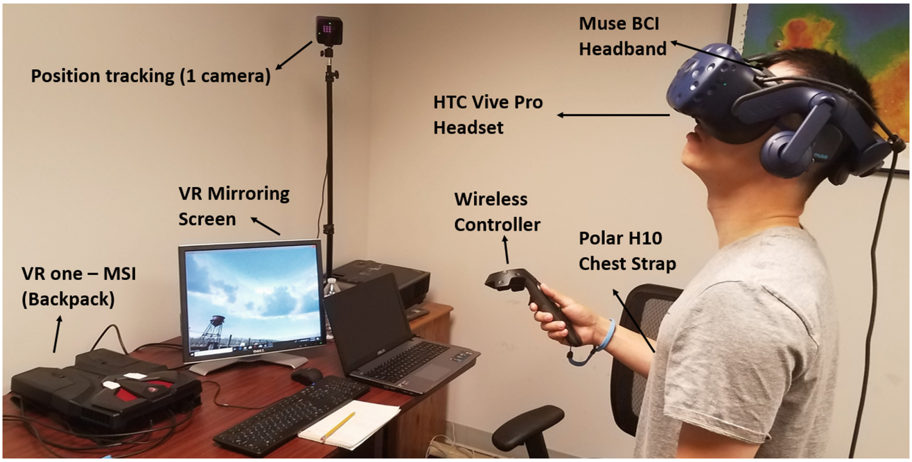

Fig. 2. System setup describing the elements used for the experiment.

For this particular characterization study, only one camera was used, since users were not required to teleport and were placed in front of the targets. We used the VR One MSI backpack computer to run the simulation, and an extra screen was used to configure the scenarios and to mirror the VR simulation (see Fig. 2).

Participants. 10 male users (ages 19–32) were voluntarily recruited for this experiment. Seven users had past experience with target shooting, six with virtual training and eight were right-handed. Before starting, users were informed about the details of the experiment which was promoted as a VR playtest, and an informed consent was individually signed.

Physiological Measurements. To measure participants' physiological responses during the interaction with the virtual simulator, cardiovascular and neurophysiological signals were synchronously recorded in a separate computer during the interaction.

Cardiovascular. The Polar H10 chest strap sensor was used to record the heartbeats during the interaction. The sensor includes onboard algorithms to compute electrocardiography (ECG) parameters needed for the HRV analysis. Mainly, it computes the R-to-R intervals (RRI) with units of 1/1024 s[3]. HR and RRIs are streamed and locally saved through a personalized Bluetooth client developed based on a Windows Bluetooth Low Energy API. To compute both time and frequency domain HRV parameters, we used the PhysioLab toolbox [29] which allows extracting the standard deviation of the RRIs (SDNN) and the root mean square of successive differences (RMSSD) values from the time domain. Similarly, parameters in the frequency domain were computed as follows: the high frequency - HF (0.15–0.40 Hz), low frequency – LF (0.04–0.15 Hz) and very low frequency – VLF (0.0033–0.04 Hz) were extracted from the Power Spectrum Density (PSD) of the RRI signal. The PSD is computed by using a Welch estimator with a Hanning window, and spectrum components are averaged by an area-under-the-curve approach. The polar chest strap has shown good accuracies for HR and RRI measurements in different scenarios including non-resting situations [30].

Neurophysiological. To record brainwave activity, the wearable Muse BCI device was used. The headband sensor includes four electroencephalography (EEG) electrodes in the TP9, Fp1, Fp2 and TP10 channel positions following the 10-20 standards. It sends raw data at a sampling frequency of 500 Hz and includes proprietary signal processing algorithms to compute α (8–12 Hz), β (12–30 Hz), ∂ (1–4 Hz), θ (4–8 Hz), and γ (30–100 Hz) bandpowers that allow the quantification of important brain activity patterns [31]. By means of a proprietary software tool (Muse Lab[4]), the power spectral density (PSD) of the EEG raw data is computed for each channel for a frequency range from 0 Hz–110 Hz. The Hamming windowing technique is used with a 90% window overlapping with a window-length of 256 samples. We were particularly interested in exploring the following EEG metrics:

- Absolute Bandpowers: which use a logarithmic function with the sum of the PSD of the EEG data in a specific frequency range. The absolute α, β, ∂, θ, and γ bandpowers were computed for the frontal electrodes of the Muse BCI sensor.
- EEG indexes: three different indexes were explored considering past investigations [32–34]. First, the Engagement index was computed by using the ratio of Beta to Alpha + Theta. The frontal asymmetry index was computed by subtracting the Alpha in Fp2 (right hemisphere) with the Alpha in Fp1 (left hemisphere). Finally, the Theta to Beta ratio was also computed to see the neurophysiological responses in those two bandpowers.

[3] https://developer.polar.com/wiki/H6,_H7,_H10_and_OH1_Heart_rate_sensors.

[4] http://developer.choosemuse.com/tools/available-data.

Questionnaires:

Perceived Task Difficulty. To measure the participants' perceived difficulty levels, we designed a 7-point Likert-type scale which will score the task difficulty as follows: 1 – extremely easy, 2 – easy, 3 – somewhat easy, 4 – moderate, 5 – somewhat hard, 6 – hard and 7 – extremely hard.

Motion Sickness. The Simulator Sickness Questionnaire was used to evaluate the level of motion sickness produced during the interaction with the VR system [35]. It evaluates two main components of the motion sickness called nausea (discomfort, salivation, sweating, dizziness, vertigo, stomach awareness, and burping) and oculomotor (fatigue, headache, eyestrain, focusing, concentration, fullness of head, vision).

Simulation Data Logging. Data from the VR simulation was recorded to compute participants' performance while shooting the virtual targets. Three main measurements were established: the total amount of shot bullets, number of destroyed targets, headshots. A shooting performance metric was considered as the ratio between the number of destroyed targets and the shot bullets.

Experimental Protocol and Data Analysis. To carry out an initial physiological characterization study in the target-shooting simulator, we designed three different scenarios that aimed at eliciting participants' responses to different difficulty levels.

Simulation Scenarios. Three difficulty modes were established during the training protocol: easy, medium and hard; each of them lasting 3 min. The *easy* configuration was set up as follows: 10 static targets randomly distributed in the ten first horizontal tracks (one target per horizontal track) of the training scenario. The *medium* configuration uses 10 moving targets at 0.5 units/s speed. Finally, the *hard* scenario used 20 moving targets at 1 units/s speed (double speed than in the *medium* difficulty). Both the target size and hardness were maintained constant across the difficulty levels, and the same Reichsrevolver was always used. The revolver was configured to have a shooting power equivalent to the target hardness, thus allowing destroying them in one shot. An initial *baseline* was also used wherein the participants' physiological signals were recorded during a passive stand-up situation, wearing the VR headset and physiological sensors, while holding the weapon without shooting or interacting with it.

Procedure. Participants were invited to interact with the system within a period lasting around 40 min (questionnaires, connections, interaction). Users were informed about the experiment details with an informed consent that was signed before starting. Then participants filled out a small demographics form and the perceived task difficulty scale was explained. The physiological sensors were next connected as well as the VR headset, and participants were instructed to grab the weapon and shoot targets to ensure they understood the process. The baseline measurements were taken during three minutes after explaining to participants the need to avoid exaggerated facial expressions, speaking or closing one of the eyes while aiming. Participants were then instructed to shoot in the *easy-medium-hard* scenarios, which were each manually set up by the researcher. A two minutes resting period was used between each scenario during which participants were asked to rate the difficulty by telling a number between one and seven. Finally, users were invited to fill out the Perceived Task Difficulty and the Simulator Sickness Questionnaire, as well as to briefly comment about the experience to finish their participation. Some sessions were video recorded to be later analyzed.

Data Analysis. Physiological data collected was processed offline using MatLab (v2013b). Individual cardiovascular and neurophysiological parameters were computed and averaged for the statistical analysis. Physiological data from one user was discarded due to human error. For the EEG bandpower and indexes analysis, we first explored the frontal Fp1 and Fp2 electrodes separately. The brainwave activity in the frontal lobe was finally weighted by averaging the contribution of both Fp1 and Fp2 electrodes. Data normality was checked by the Kolmogorov Smirnoff tests. Data with normal distributions were statistically analyzed with parametric tests while non-parametric tests were used for the non-normal distributions to determine the influence of the simulation difficulty as main effect.

2.3 Physiological and Behavioral Characterization Study Results

Perceived Difficulty and Simulation Performance. The perceived levels of difficulty were significantly affected by the pre-established simulation difficulty, $\chi^2(2) = 17.9$, $p < 0.05$. The simulation performance, $\chi^2(2) = 14.6$, $p < 0.05$ was also affected. Figure 3 shows the trends of both perceived difficulty and simulation performance across the three different simulation difficulties (values were normalized to get percentages). Notice that while the trend in the perceived difficulty is towards increasing while the simulation difficulty is increasing from easy to hard, the performance reflects an inverse relationship.

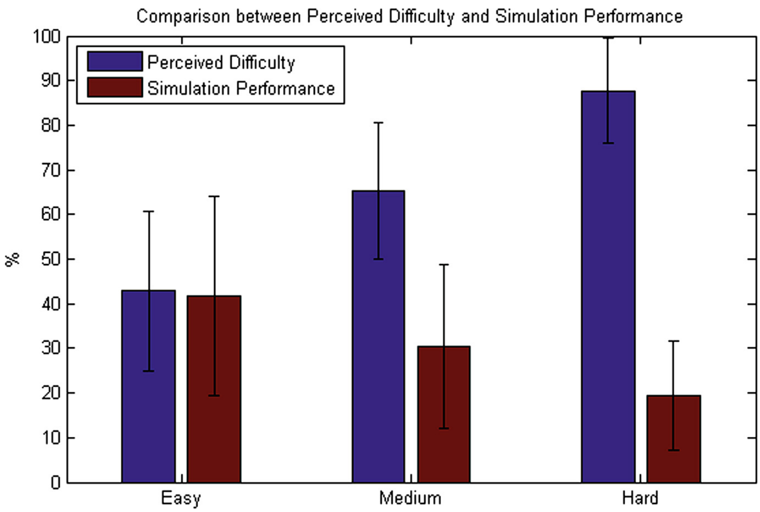

Fig. 3. Comparison between the perceived difficulty and simulation performance described in percentage.

Cardiovascular Responses. Cardiac regulation responses were quantified by means of HR and HRV parameters. Simulation difficulty significantly affected the HR levels of participants, $\chi^2(3) = 20.73$, $p < 0.05$, and the RMSSD values of the time domain HRV branch, $\chi^2(3) = 20.73$, $p < 0.05$, as shown in Fig. 4.

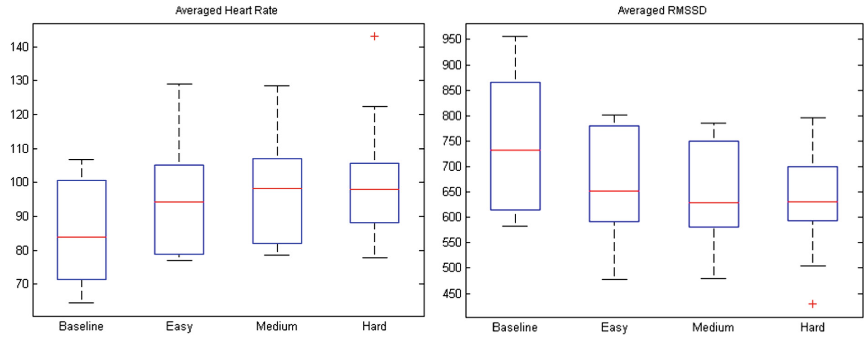

Fig. 4. HR and time-domain HRV parameters that were significantly affected by the simulation difficulty (baseline, easy, medium, hard).

The HRV frequency domain also revealed a significant effect of the simulation difficulty for the HF, $\chi^2(3) = 11.36$, $p < 0.05$, and VLF, $\chi^2(3) = 24.51$, $p < 0.05$, components. Figure 5 shows boxplots representing the differences found.

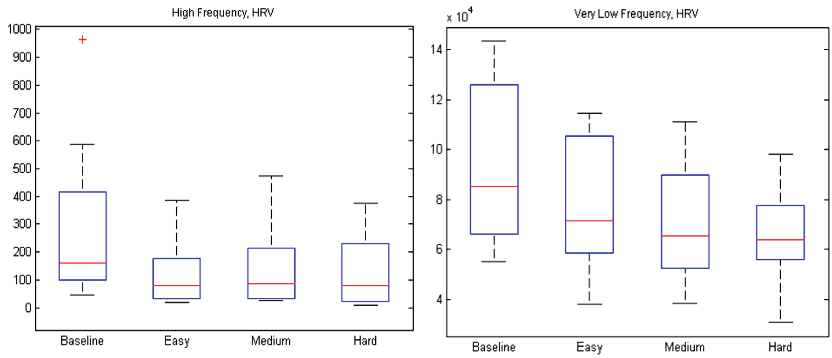

Fig. 5. Frequency-domain HRV parameters that were significantly affected by the simulation difficulty (baseline, easy, medium, hard).

Wilcoxon tests were used to follow up these findings. A Bonferroni correction was applied, so all effects are reported at a 0.0125 level of significance. Baseline HR levels, RMSSD, and VLF differed significantly from the *easy*, *medium* and *hard* simulation difficulties, $T = 45$, $r = -0.44$, while for the HF only the comparison between baseline and *easy* was significantly different, $T = 45$, $r = -0.44$.

Brain Activity Patterns. Brain activity measured in the frontal lobe using the Fp1 and Fp2 electrodes revealed significant findings for the absolute bandpowers analysis. The frontal alpha (α), $\chi^2(3) = 12.33$, $p < 0.05$, and frontal delta (∂), $\chi^2(3) = 8.73$, $p < 0.05$, were significantly affected by the simulation difficulty. Wilcoxon tests were used to follow up these findings. A Bonferroni correction was applied, so all effects are reported at a 0.0125 level of significance. Results revealed that frontal alpha (α) activity differed significantly from baseline to *easy*, $T = 44$, $r = -0.42$, baseline to *medium*, $T = 45$, $r = -0.44$ and baseline to *hard*, $T = 44$, $r = -0.42$. No significant differences were found for each individual difficulty level in the frontal delta (∂) bandpower (Fig. 6).

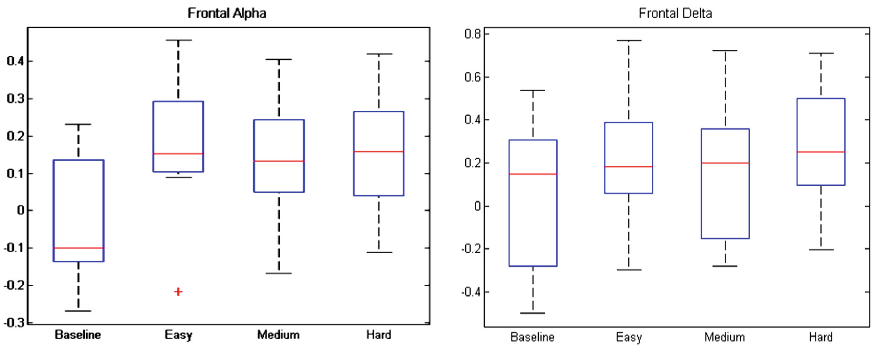

Fig. 6. Brainwave patterns significantly affected by the simulation difficulty factor.

Furthermore, after analyzing the EEG indexes in the frontal electrodes, we did not find significant main effects of the simulation difficulty in the engagement, frontal asymmetry or theta/beta indexes.

Simulation Sickness. Nausea and oculomotor domains were evaluated right after the interaction with the simulator. The oculomotor domain exhibited the highest score (M = 27.3, SD = 17.2), followed by the nausea (M = 23.8, SD = 10.3) and disorientation domains (M = 18.1, SD = 22.7). The values are lower than those reported in published papers that used virtual simulators (e.g., driving simulator [36]).

2.4 Biocybernetic Loop Design and Implementation

After processing both the qualitative and quantitative data in a complementary way, we started the design process of the BL that will be used to modulate the simulation variables automatically, based on the human states detected. Our design process was based on the methodology proposed by Fairclough and Gilleade [34], and the implementation was carried out using the BLE framework aforementioned [23]. Our BL was designed to promote optimal concentration and calmness levels during the target shooting simulation. In psychology, this can be associated with the state called *flow* or *engagement* [37] (colloquially, being “in the zone”), a state of total and optimal immersion in an activity that might optimize the users’ performance. Flow state has been previously defined regarding the bio-behavioral (psychophysiological) correlates that clearly defined the cognitive and cardiovascular descriptors of an optimal experience [38]. In our experiment, we defined three difficulty modes to investigate participants' responses to simple, moderate and frustrating shooting scenarios.

We observed that frontal alpha and delta brainwaves as well as HR and HRV (time and frequency) domain features were significantly affected by the simulation difficulty effect. We chose frontal alpha and averaged HR levels as potential features to create the real-time system, since they showed the highest levels of statistical significance in our characterization study. Figure 7 shows the designed psychophysiological model for the state of calm, concentrated and collected during the target shooting in VR. The Target Zone was defined with the physiological responses that matched the *medium* simulation difficulty scenario, where we found the highest headshots (*easy*: 5.5, *medium*: 7.4, *hard*: 4.1) and the highest performance with moving targets (*medium:* 30%, *hard:* 19%). After defining the generic formulation of our psychophysiological model, we moved to the implementation of the system's physiological intelligence layer (the BL).

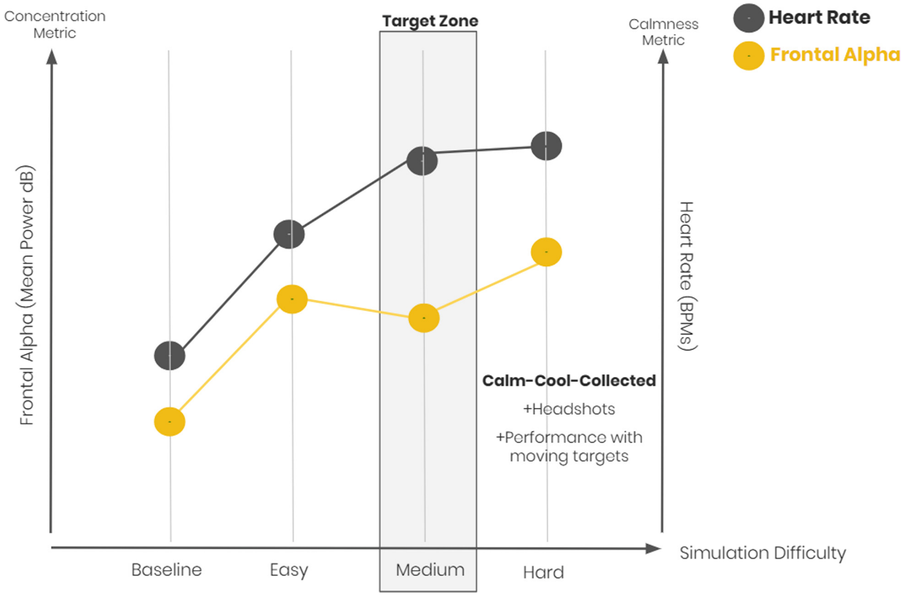

Fig. 7. Psychophysiological model for the state of Calm-Concentrated (or cool) and Collected of the target-shooting simulator in VR. Cardiovascular and neurophysiological measurements are used to compute the concentration (frontal alpha) and the calmness (heart rate) levels. The BL should persuade participants to get into a targeted zone that is where the performance of the simulator could be maximized (e.g., more headshots and better performance with moving targets).

First, the integration of the BLE was carried out via adding the game connector scripts in the target-shooting system, which allowed us to stream the simulation variables (Table 1) from the simulator to the BLE, and the physiological metrics and decisions in the adaptive rules from the BLE to the simulator. This bi-directional communication allows a more fluent exchange of data inside the game engine, reducing the risk of losing or delaying important information for the real-time BL. Multiple adaptive rules were designed and tested by means of using the BL console, a drag-and-drop programming environment incorporated in the BLE [23]. The adaptive rules can be defined by receivers, math operators and game outputs. The receivers are blocks that allow getting the physiological variables in real time from integrated sensor clients (e.g., real-time HR from the Polar H10) or from external applications (e.g., frontal alpha from Muse Lab). We defined individual adaptive rules for each of the desirable human states: calm and concentration. For those, we created array buffers of 10 s of real-time data (HR and frontal alpha EEG) that are averaged and compared against constant thresholds. Although changeable, the thresholds can be defined by seeing the frontal alpha and HR plots (Figs. 4 and 6) of the characterization study. It is worth noting that the thresholds are specifically for this virtual simulator and population. Finally, we used a logic operator block that allows the modulation of the simulation variables if and only if both concentration and calmness are at the desired levels. To modulate those variables, we used the Game Output block, which sends gradual changes (increases, decreases, etc.) to any of the simulation variables previously defined once the triggers are activated indicating that the psychophysiological states were successfully detected. Figure 8 shows one of the adaptive rules designed where we used 0.1 dB (concentration, frontal alpha) and 110 BPMs (calmness, HR) as thresholds for triggering target speed and raining intensity, respectively. The magnitude

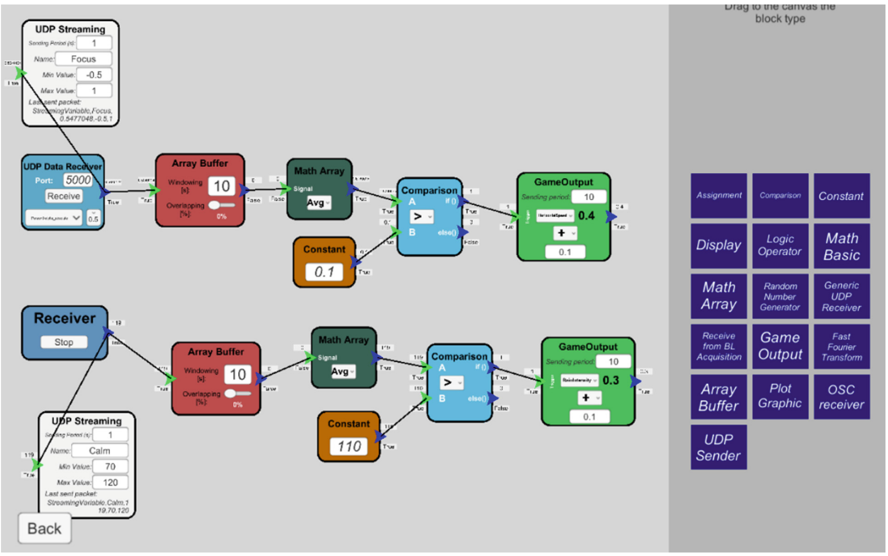

Fig. 8. Physiologically adaptive rules created in the BLE for experimentation. The adaptive rules can be seen as functional pipelines of processed data that triggers the modulation in the VR simulator.

of the change was defined as 0.1 for each simulation variable. The modulations are carried out in windows of 10 s allowing participants to improve or sustain their self-regulation strategies while shooting.

Figure 8 illustrates one of the multiple adaptive rules that can be created for training concentration and calmness in the *BioPhyS* simulator. Changes can be made on the fly, allowing a dynamic modification of thresholds values, simulation variables to be modulated, processing window's lengths, and others. Thus, the final integrated system can be used for testing multiple versions of the BLs which will allow a fast convergence to a stable physiologically adaptive system that maximizes training outcomes.

3 Guidelines for Biocybernetic Adaptation in Virtual Reality

After our initial conceptualization and development process of a biocybernetic system able to promote both concentration and calmness levels in the target-shooting simulator, we reflected on a set of relevant learnings that can be crucial in the integration of biocybernetic adaptation in VR applications. Although not extensive, we hope they can be used as a first milestone towards more widespread use of physiological intelligence in novel immersive media.

- **Before Starting, Answer the WHY of using BLs into Your VR Application.** Although there is much enthusiasm in regards of using physiological intelligence to enhance VR experiences, it might be important to take some time to analyze with the research/development team to know whether or not the BL is the most appropriate framework to approach. In our initial brainstorming process, we realized that some of the closed loop ideas might be transformed into potential products just by using simple biofeedback methods as a way to visualize user's inner states instead of having to go through the complete collection-analysis-translation model of BLs. In our case, there are very specific and already established guidelines that correlate psychophysiological states with improvements in shooting performance [22, 39, 40].
- **Define a Psychophysiological Model with Real Data before Moving to the Real-time System Implementation.** Carrying out a controlled experiment with physiological sensing in VR can be a very demanding task (e.g. sensor intrusiveness, VR system preparation, users recruitment, etc.). Nevertheless, this turns out to be a crucial preliminary step to better understand psychophysiological responses of users during immersive experiences in VR. Several assumptions can be wrongly used to drive the BL design process, producing very disappointing and confusing closed loop systems. In our case, we briefly entertained the idea that the optimal performance state in a stressful shooting scenario would simply be a low arousal state. This belief was empirically refuted by observation of the actual psychophysiological responses shown to correspond to effective shooting performance. Our psychophysiological model (see Fig. 7) allowed us a streamlined construction of the adaptive rule in the biocybernetic console of the BLE, including threshold values, windows for signal processing and math operators needed for a steady functioning of the real-time system.

- **Delimit the Adaptation Strategy and the Expected Benefits of the BL.** Although several projects have explored the use of physiological computing technologies to bring unique immersive VR experiences, attention has been mostly paid to either mirroring the signals to be displayed in the VR environment (conventional biofeedback) or using the physiological signals as control input [4, 24, 41]. Biocybernetic adaptation constitutes a more sophisticated use of interpreted psychophysiological states, and it must be interpreted as an adaptation layer of the VR application. That means that the VR application should be able to work independently without the BL. Theoretically, once integrated, the BL might have the potential to enhance the user's performance on pre-defined tasks by promoting physiological self-regulation skills (see BL evaluation stage [34]). In the *BioPhyS* simulator, we aimed at improving concentration and calmness during shooting scenarios via controlled respiration that will help at regulating cardiovascular responses and increase the frontal alpha activity.
- **Clearly Define the VR Game/Simulation Variables and Value Ranges to Be Modulated by Means of the BL.** Although there are endless variables that can be used for the physiological modulation in a VR application, a previous and clear definition of specific variables and ranges for testing different prototypes of the BL will ensure that you are not simply picking up the first and most evident of the virtual modulation parameters. In the integration with the BLE, it is recommended to let the software know the particular ranges within each simulation variable can be modulated in order to avoid redundancies or possible miscommunications between the entities (BLE and VR application). In our design process, we brainstormed and initially considered several variables that are not included in Table 1 (e.g., time manipulation, distractors, power-ups). In the implementation, due to time constraints, we decided to prioritize those simulation variables that allowed us to create comprehensible and intuitive metaphors (e.g., calmness and raining, concentration and target speed).
- **Avoid Generalizations.** As described before, each population should be modeled regarding the context and the specificities of the VR application. There are no generalizable psychophysiological models that can be transversally used from one population to the other in different contexts [42]. Additionally, VR raises very particular challenges regarding biocybernetic adaptation research since psychophysiological correlates have been inadequately explored with novel and highly immersive state-of-the-art VR hardware [38, 43–45].

4 Discussion and Future Work

After an intense and structured process of integrating VR and biocybernetic adaptation technologies in a functional prototype for a military-oriented company, we demonstrated how it is possible to create replicable physiologically adaptive systems by using state-of-the-art knowledge and tools. First, developing VR simulations is nowadays a very streamlined process where many 3D assets and tools for interaction design can speed up the prototyping process. Additionally, the use of such a very specialized and integrative software tool as the BL Engine aided in the incorporation of biocybernetic adaptation through an efficient and straightforward methodology. This tool streamlines the process of integrating the physiological signals into the game engine and extracting the features needed for the real-time modulation, enabling system designers to devote more time and effort to designing adaptations based upon detection of the human states and to how this information can be used to influence end-users.

The BL Engine tool automates the construction of algorithms that determine what and how physiological changes are reinforced by task adaptation changes. Stephens and colleagues [46] introduce the idea that, in addition to driving real-time adaptations that reward learning of self-regulation skill, the adaptation algorithms themselves could be periodically modified (e.g., higher thresholds) based upon longer time course changes that reflect a trainee's emerging ability to voluntarily control physiological parameters. In the *BioPhyS* project, the *Woz* configuration console implements a manual version of this capability by enabling trainers to modify the simulation variables during the interaction. Without this capability, the physiological modulation method would not take into account the likelihood that the physiological self-regulation behavior and skill of a trainee changes as training progresses. Fuchs and Schwarz [47] identify a method without this capability as a "hard-coded" adaptation strategy, where the system triggers a predetermined adaptation strategy.

From a psychophysiological point of view, the results of our characterization study revealed significant evidence of how users respond to VR shooting simulators. Past experiences using immersive virtual environments have found changes in Alpha oscillatory activity during aiming that are associated with better performance while shooting [48]. In our experiment, we found the frontal Alpha activity (as well as the Delta) to be a brainwave pattern that clearly allows the differentiation between baseline and active shooting states in our VR simulator. Furthermore, increases of Alpha EEG activity have also been associated with subjects who performed well in spatial navigation tasks in a VR environment [49]. Past research also suggested how to use Alpha-related activity to create modulations in a BCI version of the popular World of Warcraft videogame [50]. In summary, Alpha oscillatory activity resulted in a sensitive biomarker to create real-time adaptations that accurately reflected users' concentration levels during target shooting tasks in the *BioPhyS* simulator.

Autonomic cardiac regulation has also been studied in VR experiences demonstrating how VR simulations can shape the cardiovascular responses of users. Significant difference in HR values was found during 5-min long interactions with a VR experience that required users to perform simple manual tasks involving the arrangement of virtual elements with multiple shapes [51]. Similarly to our easy-medium-hard difficulty levels, an experiment with a VR first-person-shooter experience showed non-significant differences for the main effect condition (boredom-flow-frustration) on the users' heart rate [43]. We believe that the novel room-size VR tracking used for the *BioPhyS* simulator may significantly affect the cardiovascular responses in VR experiences. Additionally, after exchanging information with professional police officers' trainers, we learned that some specific sympathetic responses are desired during military fighting situations that can be used as target states to create the BLs (e.g., 100–115 BPMs for HR levels) [52]. A similar concept was used to persuade older users to exert in targeted cardiac zones via biocybernetic adaptation strategies integrated during exercise-based videogames also called Exergames [53].

For future work, we are planning to compare the initial results found with the young male population assessed against a group of trained police officers. We have recorded police officers who went through the same data collection protocol, and now we are building a psychophysiological model for this population. Our initial hypothesis proposes a more controlled cardiac regulation behavior as well as different brainwave activation patterns. A very detailed description of the project design and development can be found at https://sites.google.com/view/johnhci/simulators/biophys.

5 Conclusion

Biocybernetic adaptation technologies are poised to exploit the very fast adoption of VR technologies that are now ubiquitous and accessible. With novel physiologically aware systems, the training process of any skill in a virtual environment can benefit from a more personalized and informed content delivery that has the potential to maximize the learning outcomes. The *BioPhyS* approach here presented, evidences how biocybernetic technologies can be meaningfully integrated with VR military training simulators to produce physiologically intelligent systems able to sharpen trainees' self-regulation capabilities. Those skills might impact the performance of daily worklife tasks (such as firing in the case of police officers), helping users to respond in a more controlled and physiologically regulated way to external stressors. We conclude our project, highlighting the potential of using biocybernetic adaptation in various VR scenarios that are now booming such as virtual rehabilitation, wellbeing promotion, pain treatment, and education. Moreover, we emphasize the benefits of this VR-biocybernetics symbiosis, which aids the creation of more adaptive VR systems and promotes a less tedious training process of physiological regulation skills.

Acknowledgments. Authors would like to thank: (i) the J&F Alliance Group who financially supported the internship and VR development process, (ii) the National Institute of Aerospace (NIA) that supported the convergence of the stakeholders for this project, (iii) the PRISM team from NASA Langley for his very supportive feedback throughout the project development and (iv) Zeltech employees at Hampton facilities. Special thanks to personnel from the Hampton Police Department who participated actively in our studies; and Jeremy Sklute and Mike Priddy from J&F Alliance who helped in improving the system's realism.

Contributions. JEM and ATP designed and defined the *BioPhyS* approach and the biocybernetic adaptation strategies. LEV developed the VR simulation and carried out the integration with the BL Engine. All authors revised and approved the current version of the manuscript.

References

1. Anthes, C., García-Hernández, R.J., Wiedemann, M., Kranzlmüller, D.: State of the art of virtual reality technology (2016)

2. Jerald, J.: The VR Book: Human-Centered Design for Virtual Reality. Morgan & Claypool, New York (2015)
3. Kosunen, I., Salminen, M., Järvelä, S., Ruonala, A., Ravaja, N., Jacucci, G.: RelaWorld: neuroadaptive and immersive virtual reality meditation system. In: Proceedings of the 21st International Conference on Intelligent User Interfaces, pp. 208–217. ACM (2016)
4. Sra, M., Xu, X., Maes, P.: BreathVR: leveraging breathing as a directly controlled interface for virtual reality games. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, p. 340. ACM (2018)
5. Muñoz, J.E., Paulino, T., Vasanth, H., Baras, K.: PhysioVR: a novel mobile virtual reality framework for physiological computing. In: 2016 IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom), pp. 1–6. IEEE (2016)
6. Pope, A.T., Stephens, C.L., Gilleade, K.: Biocybernetic adaptation as biofeedback training method. In: Fairclough, S.H., Gilleade, K. (eds.) Advances in Physiological Computing. HIS, pp. 91–115. Springer, London (2014). https://doi.org/10.1007/978-1-4471-6392-3_5
7. Fairclough, S.H.: Fundamentals of physiological computing. Interact. Comput. **21**, 133–145 (2009)
8. Novak, D., Mihelj, M., Munih, M.: A survey of methods for data fusion and system adaptation using autonomic nervous system responses in physiological computing. Interact. Comput. **24**, 154–172 (2012)
9. Fairclough, S.H.: Physiological computing and intelligent adaptation. In: Emotions and Affect in Human Factors and Human-Computer Interaction, pp. 539–556. Elsevier (2017)
10. Burdea, G.C., Coiffet, P.: Virtual Reality technology. Wiley, Hoboken (2003)
11. Kennedy, R.S., Stanney, K.M., Lawson, B.D.: Capability of virtual environments to meet military requirements. Essex Corp., Orlando, FL (2000)
12. Mead, C.: War Play: Video Games and the Future of Armed Conflict. Houghton Mifflin Harcourt, Boston (2013)
13. Roy, M.J., Rizzo, A., Difede, J., Rothbaum, B.O.: Virtual reality exposure therapy for PTSD. In: Complementary and Alternative Medicine for PTSD, p. 271 (2016)
14. Wood, D.P., et al.: Cost effectiveness of virtual reality graded exposure therapy with physiological monitoring for the treatment of combat related post traumatic stress disorder. Stud. Health Technol. Inform. **144**, 223–229 (2009)
15. Ćosić, K., Popović, S., Kukolja, D., Horvat, M., Dropuljić, B.: Physiology-driven adaptive virtual reality stimulation for prevention and treatment of stress related disorders. Cyberpsychology Behav. Soc. Netw. **13**, 73–78 (2010)
16. Blacker, K.J., Hamilton, J., Roush, G. et al.: Cognitive training for military application: a review of the literature and practical guide. J. Cogn. Enhanc. **3**, 30 (2019). https://doi.org/10.1007/s41465-018-0076-1
17. Lele, A.: Virtual reality and its military utility. J. Ambient. Intell. Hum. Comput. **4**, 17–26 (2013)
18. Palsson, O.S., Harris Sr, R.L., Pope, A.T.: Method and apparatus for encouraging physiological self-regulation through modulation of an operator's control input to a video game or training simulator (2002)
19. Prinzel III, L.J., Pope, A.T., Palsson, O.S., Turner, M.J.: Method and apparatus for performance optimization through physical perturbation of task elements (2014)
20. Pope, A.T., Stephens, C.L., Jones, C.A.: Method and system for physiologically modulating action role-playing open world video games and simulations which use gesture and body image sensing control input devices. Google Patents (2015)
21. Pope, A.T., Stephens, C.L., Blanson, N.M.: Physiologically modulating videogames or simulations which use motion-sensing input devices (2014)

22. Sajnog, C.: How to Shoot Like a Navy Seal: Combat Marksmanship Fundamentals. Center Mass Group, LLC (2013)
23. Muñoz, J.E., Rubio, E., Cameirao, M., Bermúdez, S.: The biocybernetic loop engine: an integrated tool for creating physiologically adaptive videogames. In: 4th International Conference in Physiological Computing Systems, Madrid, España (2017)
24. Bontchev, B.: Adaptation in affective video games: a literature review. Cybern. Inf. Technol. **16**, 3–34 (2016)
25. Jacucci, G., Fairclough, S., Solovey, E.T.: Physiological computing. Computer **48**, 12–16 (2015)
26. Vourvopoulos, A., Faria, A.L., Cameirão, M.S., Bermudez i Badia, S.: RehabNet: a distributed architecture for motor and cognitive neuro-rehabilitation. In: 2013 IEEE 15th International Conference on e-Health Networking, Applications Services (Healthcom), pp. 454–459 (2013)
27. Fisher, J.G., Hatch, J.P., Rugh, J.D.: Biofeedback: Studies in Clinical Efficacy. Springer, Boston (2013)
28. Johnson, B.R.: Crucial Elements of Police Firearms Training. Looseleaf Law Publications (2007)
29. Muñoz, J.E., Gouveia, E.R., Cameirão, M.S., i Badia, S.B.: PhysioLab-a multivariate physiological computing toolbox for ECG, EMG and EDA signals: a case of study of cardiorespiratory fitness assessment in the elderly population. Multimed. Tools Appl., 1–26 (2017)
30. Plews, D.J., Scott, B., Altini, M., Wood, M., Kilding, A.E., Laursen, P.B.: Comparison of heart-rate-variability recording with smartphone photoplethysmography, Polar H7 chest strap, and electrocardiography. Int. J. Sport. Physiol. Perform. **12**, 1324–1328 (2017)
31. Sanei, S., Chambers, J.A.: EEG Signal Processing. Wiley, Hoboken (2013)
32. McMahan, T., Parberry, I., Parsons, T.D.: Evaluating electroencephalography engagement indices during video game Play. In: FDG (2015)
33. Kamzanova, A.T., Matthews, G., Kustubayeva, A.M., Jakupov, S.M.: EEG indices to time-on-task effects and to a workload manipulation (cueing). World Acad. Sci. Eng. Technol. **80**, 19–22 (2011)
34. Fairclough, S., Gilleade, K.: Construction of the biocybernetic loop: a case study. In: Proceedings of the 14th ACM International Conference on Multimodal Interaction, p. 578. ACM, New York (2012)
35. Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G.: Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int. J. Aviat. Psychol. **3**, 203–220 (1993)
36. Teasdale, N., Lavallière, M., Tremblay, M., Laurendeau, D., Simoneau, M.: Multiple exposition to a driving simulator reduces simulator symptoms for elderly drivers (2009)
37. Csikszentmihalyi, M.: Toward a psychology of optimal experience. Flow and the Foundations of Positive Psychology, pp. 209–226. Springer, Dordrecht (2014). https://doi.org/10.1007/978-94-017-9088-8_14
38. Peifer, C.: Psychophysiological correlates of flow-experience. In: Engeser, S. (ed.) Advances in Flow Research, pp. 139–164. Springer, New York (2012). https://doi.org/10.1007/978-1-4614-2359-1_8
39. Sandweiss, J.H.: Biofeedback and sports science. In: Sandweiss, J.H., Wolf, S.L. (eds.) Biofeedback and sports science, pp. 1–31. Springer, Boston (1985). https://doi.org/10.1007/978-1-4757-9465-6_1
40. Grossman, D.: On Killing: The Psychological Cost of Learning to Kill in War and Society. Open Road Media, New York (2014)

41. Dey, A., Piumsomboon, T., Lee, Y., Billinghurst, M.: Effects of sharing physiological states of players in a collaborative virtual reality gameplay. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, pp. 4045–4056. ACM (2017)
42. Cacioppo, J.T., Tassinary, L.G., Berntson, G.: Handbook of Psychophysiology. Cambridge University Press, Cambridge (2007)
43. Bombeke, K., et al.: Do not disturb: psychophysiological correlates of boredom, flow and frustration during VR gaming. In: Schmorrow, D.D., Fidopiastis, C.M. (eds.) AC 2018. LNCS (LNAI), vol. 10915, pp. 101–119. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-91470-1_10
44. Pugnetti, L., Meehan, M., Mendozzi, L.: Psychophysiological correlates of virtual reality: a review. Presence Teleoperators Virtual Environ. **10**, 384–400 (2001)
45. Wiederhold, B.K.: Virtual reality and applied psychophysiology. Appl. Psychophysiol. Biofeedback **30**, 183–185 (2005)
46. Stephens, C., et al.: Biocybernetic adaptation strategies: machine awareness of human engagement for improved operational performance. In: Schmorrow, Dylan D., Fidopiastis, Cali M. (eds.) AC 2018. LNCS (LNAI), vol. 10915, pp. 89–98. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-91470-1_9
47. Fuchs, S., Schwarz, J.: Towards a dynamic selection and configuration of adaptation strategies in augmented cognition. In: Schmorrow, D.D., Fidopiastis, C.M. (eds.) AC 2017. LNCS (LNAI), vol. 10285, pp. 101–115. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-58625-0_7
48. Pereira, M., Argelaguet, F., Millán, J. del R., Lécuyer, A.: Novice shooters with lower pre-shooting alpha power have better performance during competition in a virtual reality scenario. Front. Psychol. **9**, 527 (2018)
49. Pugnetti, L., Mendozzi, L., Barberi, E., Rose, F.D., Attree, E.A.: Nervous system correlates of virtual reality experience. In: European Conference on Disability, Virtual Reality and Associated Technology (1996)
50. Friedman, D.: Brain-computer interfacing and virtual reality. In: Nakatsu, R., Rauterberg, M., Ciancarini, P. (eds.) Handbook of Digital Games and Entertainment Technologies, pp. 1–22. Springer, Singapore (2015). https://doi.org/10.1007/978-981-4560-52-8_2-1
51. Malińska, M., Zużewicz, K., Bugajska, J., Grabowski, A.: Heart rate variability (HRV) during virtual reality immersion. Int. J. Occup. Saf. Ergon. **21**, 47–54 (2015)
52. Mason, P.H.: Recovering from the War: A Guide for All Veterans, Family Members. Friends and Therapists. Patience Press, High Springs (1998)
53. Muñoz, J.E., Rubio, E., Cameirao, M.S., Bermúdez i Badia, S.: Closing the loop in exergaming - health benefits of biocybernetic adaptation in senior adults. In: Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play (2018)