Impact of Different Stimuli on User Stress During a Virtual Firefighting Training Exercise

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***Abstract*—Training firefighters using Virtual Reality (VR) technology brings several benefits over traditional training methods including the reduction of costs and risks. The ability of causing the same level of stress as a real situation so that firefighters can learn how to deal with stress was investigated. An experiment aiming to study the influence that additional stimuli (heat, weight, smell and using personal protective equipment-PPE) have on user's stress level while performing a Virtual Environment (VE) designed to train firefighters was developed. Participants' stress and Heart Rate Variability (HRV) were obtained from electrocardiograms recorded during the experiment. The results suggest that wearing the PPE has the largest impact on user's stress level. The results also showed that HRV was able to evidence differences between two phases of the experiment, which suggests that it can be used to monitor users' quantified reaction to VEs.**

Keywords—virtual reality, firefighter training, heart rate variability, stress

I. Introduction

Training plays an important role in all types of professions. In the case of firefighters and other emergency services, training is even more important given the need that they have to train repeatedly in order to obtain and maintain their skills [1]. The training of professionals using Virtual Reality (VR) is not a new subject, one of the initial purposes for which VR was developed was for the training of professionals [2]. The interest in the use of Virtual Environments (VE) for training arises naturally from the advantages that they offer when compared to traditional training methods, such as: reduction of costs and risks [3], [4].

This work presents an experiment where a VE designed to train firefighters was used to study the influence of several additional stimuli on participants' stress. Stress was measured by analyzing five parameters of Heart Rate Variability (HRV), Table 1 presents a description of the parameters used together with their trends under stress, as identified in Castaldo et al. [5] meta-analysis. These parameters were extracted from electrocardiograms recorded by the participants during the experiment. The main goal of this work was to identify the impact of the mentioned stimuli on the participant's physiological response, namely on stress observed through HRV.

The identification of stimuli that can generate a higher level of stress is a relevant contribution because, in certain training situations, the existence of stress is an important factor for it to be successful. The idea is that a person who is under training is repeatedly exposed to the level of stress they will face in the real world so that they learn to deal with it and learn to have greater control over that stress.

The case study used in this work was a firefighter training exercise. The exercise consists of a virtual replica of a training exercise that is used in the training of novice firefighters and its objective is to accustom future firefighters to the conditions they commonly face in urban and industrial fires.

TABLE I. Description of the HRV variables used and their trend under stress [5].

Domain	Variable	Description	Trend under stress (N = 758)
Time	AVNN	Average of Normal-to-Normal beat time distance (NN) intervals (ms)	↓
	SDNN	Standard deviation of NN intervals (ms)	↓↑
	RMSSD	Root mean square of differences of successive NN intervals (ms)	↓
	pNN20	Proportion of NN variations above 20 ms (%)	↓
Frequency	LF / HF	Ratio of LF and HF frequency power bands	↑

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II. Related Work

The literature presents a few works that have studied the influence of a VE on the user's cardiac response. Some of these assessed only the Heart Rate (HR) while others went further and assessed participants' HRV.

To the best of the authors' knowledge, the first work to study the influence of a VE on the user's HR was Dillon et al. [6]. The authors conducted an experiment with 119 participants where the format and content of the media presented in a VE was varied among participants. The results indicated limited usefulness of HR, being able to show a significant difference between different media content but not between different media formats. Another study that assessed the user's HR in a VE was Wiederhold et al. [7]. In this work, the authors measured the percentage change in HR. They carried a study in which 79 participants were exposed to a VE that simulated an airplane flight. The results indicated that the percentage difference in the participants' HR was smaller as the reported feeling of presence was greater and that HR was not able to differentiate participants who were identified as phobic from non-phobic. In view of these results, Wiederhold et al. [7] stated that more sensitive measures such as HRV should be used. A work where the HR was successful in discriminating participants from different conditions was Meehan et al. [8]. In this work, a stressful VE (presenting a virtual pit) and 95 participants were used to study the influence of multiple exposures, passive haptics and frame rate on the participants' HR. The results showed that HR was able to distinguish participants from different conditions, thus supporting the use of HR to monitor users' response to stressful VEs.

Using two VEs, one presenting a driving scenario and the other an airplane flight scenario, Jang et al [9] carried out an experiment where the HRV of 11 participants was compared between the two environments. The results showed no significant differences in any of the HRV parameters measured, however, both environments caused a significant increase in the LF / HF parameter. The authors stated that this increase was caused by the participants 'exposure to a new stimulus. The work of Zimmons et al. [10] presented a similar result, the authors used the same stressful VE as [8] and conducted an experiment with 55 participants where the goal was to study the influence of the visual quality of a VE on the participants' HR. The results showed that the HR was similar between conditions but that there was a significant increase in it when compared to the HR displayed by the participants during a previous training phase of the experiment where they were exposed to a non-stressful VE.

To investigate whether a participant's HR and HRV could be used to evidence changes in an VE, Slater et al. [11] carried out an experiment where 20 participants were exposed to a VE that presented a noisy bar scenario. Like other works, the experiment had two phases, an initial training one and an experimental one. In the experimental phase, at certain times the VE illusion was broken through whiteouts induced in the VE in order to cause a reaction in the user. The results showed that the HR and HRV were successful in distinguishing the two phases of the experiment and in highlighting the whiteouts induced during the VE. Considering the results, the authors indicated that the user's cardiac response could be used to monitor its reaction to a VE. Using a non-stressful VE, Brogni et al. [12] carried out a study in which the HRV of 40 participants was analyzed. The experience had several phases, including a training and an experimental one, and the VE simulated an urban scenario where some virtual characters walked. The results showed that stress typically increased during the initial training phase and towards the end of the experimental phase. According to the authors, the greatest contribution of the work was the indication that HRV can be used to analyze the behavior of participants during a VE.

Using a stressful VE similar to [8], Slater et al. [13] carried out an experiment where the impact of the realism of a VE on the HRV of 33 participants was studied. To vary the level of realism, two lighting techniques were used: recursive ray casting and ray tracing. The results showed a significant difference between conditions, indicating that the ray tracing lighting technique caused a higher level of stress. To verify whether this increase in stress was caused by the lighting technique or by the dynamic effects provided in the ray tracing technique (shadows and reflections), a second study was conducted, this time using a non-stressful VE and 21 participants [14]. In this study, the VE scenario was a small library and both lighting techniques provided the same dynamic effects of shadow and reflection. The results showed that there were no significant differences, which led the authors to conclude that the cause of increased stress in the first experiment was the dynamic effects and not the lighting technique.

More recently, Deniaud et al. [15] carried out an experiment with 14 participants where the influence of the level of visual realism and degree of visibility of a VE on user's HRV was studied. The VE presented a driving scenario where the participants had to follow a certain car. The results suggested that a higher level of realism causes greater physiological activation compared with a low level of realism and that the degree of visibility has no influence on it. Finally, motivated by the emergence of high performance and low-cost HMDs, Egan et al. [16] carried out an experiment with 33 participants that aimed to study the influence of a VE visualization method (VR vs non-VR) on the user's HR. The results showed that HR was not able to distinguish between conditions, which suggests that HR alone is not able to distinguish different media formats, and which is consistent with the work of Dillon et al. [6].

In general, the literature seems to indicate that the user's cardiac response can be used to measure its reaction to a VE. In addition, it seems to suggest that better results are obtained when using a stressful VE and when the user's response is monitored through HRV instead of just HR. This work follows both suggestions, using a VE of a stressful nature and measuring the response of users through their HRV. The research question that this paper aims to answer is: "What is the impact that different stimuli have on the physiological response of users in a VE?". To help answer this question, the authors defined the following specific goals: to compare the HRV of participants exposed to

different stimuli during virtual training; to compare the HRV of participants between two phases of the experiment; and to compare stress and fatigue, measured subjectively, among participants exposed to different stimuli during virtual training.

III. Materials and Methods

This paper presents a comparative cross-sectional study that follows a between-subject design, as described next.

A. Variables

The independent variable (IV) of this study is the Stimuli. The IV is composed of four levels: audiovisual, audiovisual + smell, audiovisual + heat, audiovisual + weight, and audiovisual + PPE.

The dependent variables are the perceived stress, perceived fatigue, and participant's stress (Observed through HRV parameters AVNN, SDNN, RMSSD, pNN20, and LF / HF; see Table I).

B. Sample

The sampling technique adopted was the non-probabilistic convenience sampling procedure. The sample is composed by 65 participants (41 male, 24 female) aged between 24 and 21 (M = 24.05, SD = 4.32) All the participants reported normal (N = 39) or corrected to normal vision (N = 26). All participants reported normal hearing. The participants were randomly distributed between the different levels of the IV, resulting in the following distribution:

- Audiovisual: 12 participants;
- Audiovisual + smell: 12 participants;
- Audiovisual + heat: 14 participants;
- Audiovisual + weight: 14 participants;
- Audiovisual + PPE: 13 participants.

C. Instruments

Four instruments were used to measure the dependent variables of this study:

- A Portuguese version of the Perceived Stress Scale (PSS) [17], for assessing participants' perceived stress;
- A Portuguese version of the 20-item Checklist Individual Strength (CIS) questionnaire [18], for assessing participants' perceived fatigue;
- Visual Analogue Scales (VAS), one-item scales where the user evaluates the amount of a given characteristic/attitude on a level of 1 to 10 [19], [20];
- HRV parameters, to objectively assess participants' stress in different moments of the experiment.

In addition, a socio-demographic questionnaire was applied before the experiment to obtain data such as age, sex and level of experience with VR.

D. Materials and Apparatus

Two VEs were used in this experiment: a habituation environment and a virtual exercise environment. The habituation VE presented an urban scenario and its goal was simply to acclimate the user to the technology. The virtual exercise VE consisted of virtual replica of a real-world firefighter training exercise that aims to prepare firefighters for fire situations that occur in urban and industrial fires. The habituation VE lasted for 5 minutes while the virtual exercise VE lasted for around 15 minutes.

For delivering the visual stimulus, an HTC VIVE HMD was used. The sound stimulus was delivered via Bose QuietComfort 25 headphones with noise-cancelling technology. Depending on the experimental condition, different equipment was used to deliver the different stimulus. For delivering smell, a SensoryCo SmX-4D aroma system was used. The smell used was labelled by the manufacturer as "burnt wood". To avoid smell saturation and deliver a credible smell experience, the system was calibrated by the research team resulting in a smell delivery of 0.5 second bursts at every 30 seconds. The heat stimulus was provided through an air conditioning system that was pre-programmed for maintaining the room temperature at 29ºC and a fan heater to simulate the fire source. The weight stimulus was achieved by using a Self-Contained Breathing Apparatus (SCBA) that is used by firefighters and that consists of oxygen bottles mounted on the back of the participants. The PPE stimulus was provided by making participants wear actual firefighters' PPE which also included the SCBA used in the weight condition.

The participant's head was tracked with the HTC VIVE HMD whilst his hands and feet were tracked by an OptiTrack motion capture system. To track his hands and feet, gloves and shoe-wraps equipped with reflective markers were used. These five tracking points were used to mimic the participant's movements in their avatar in the VE taking

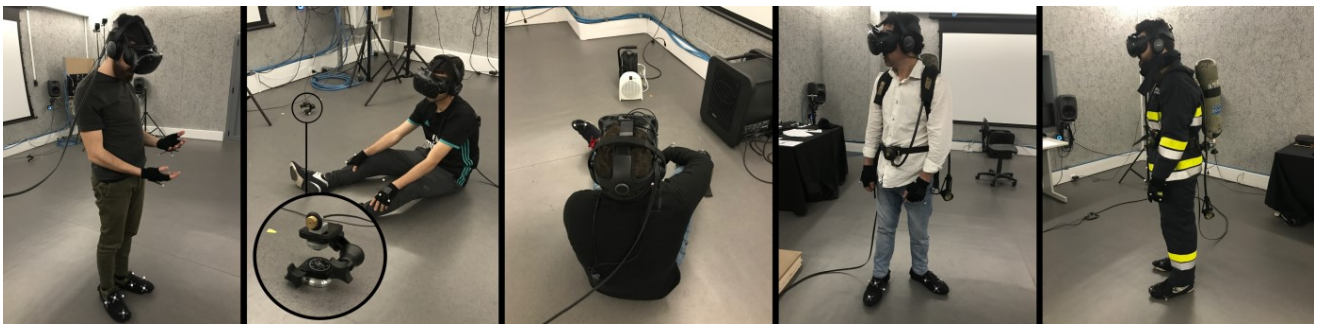

Figure 1. Illustration of the different equipment used in each group. From left to right, audiovisual (control condition), audiovisual + smell, audiovisual + heat, audiovisual + weight, audiovisual + PPE.

advantage of inverse kinematics. The equipment used in each group is illustrated in Fig. 1. For collecting the physiological data, a VitalJacket® [21] was used, which consists of a wearable biomonitoring platform in the form of a t-shirt that is able to capture medical-grade electrocardiogram exams in real-time.

E. Experimental Procedure

The study took place at the MASSIVE Laboratory. If the participant agreed to participate in the experiment, he/she was asked to sign a consent form. After signing the consent form, the researcher asked the participant to equip the VitalJacket® in his privacy.

After equipping the Vital Jacket®, the researcher verified if the Vital Jacket® was properly equipped and recording the participant's HRV. After this verification, the participant was asked to complete a pre-questionnaire that was composed by the socio-demographic, PSS and CIS questionnaires as well as VAS of fatigue and stress. After completing the pre-questionnaire, the participant was forwarded to the baseline measurement. The baseline measurement consisted simply of asking the participant to stay seated alone in the experimental room for 15 minutes while listening to a relaxing audio clip. This task took 15 minutes because the goal was to compare this baseline response with the participant's response during the VE exercise, hence the importance of having a similar duration.

After 15 minutes, the researcher helped the participant to equip the HMD, headphones, shoe-wraps and gloves. At this time, the participant was exposed to the habituation VE, which lasted for 5 minutes. After this habituation to technology, the participant filled in the VAS again to measure his perception of fatigue and stress before the virtual exercise. After completing the questionnaire, the participant put back the equipment needed to perform the virtual exercise, which lasted around 15 minutes. After performing the virtual exercise, the researcher helped the participant to remove the equipment and asked him/her to fill the VAS for fatigue and stress a third and last time. After filling in the VAS, the participant's last task was to remove the VitalJacket®.

VAS's were applied a total of three times, one at the beginning of the experiment, one before the virtual exercise and one after the virtual exercise. In the results section, the results of these questionnaires are labeled as VAS1, VAS2 and VAS3. The whole procedure took, on average, 1 hour and 10 minutes per participant.

F. Statistical procedure

Because physiological responses can vary greatly from person to person, non-parametric statistics were used, allowing the authors to use the full sample for the statistical tests.

Kruskal-Wallis H tests were performed to determine if there were significant differences in fatigue and stress between the five groups of participants. When significant differences between groups were shown, pairwise comparisons were performed as a post-hoc analysis using Dunn's [22] procedure with a Bonferroni adjustment. In addition, mean ranks were presented to identify which groups showed lower and higher values.

Wilcoxon signed-ranks tests were also used to compare HRV parameters between the baseline and virtual exercise moments of the experiment.

The results were interpreted as statistically significant if the p-value was lower than 0.05 and indicative if between 0.05 and 0.10.

IV. RESULTS

From the initial sample (N = 65), six participants were removed because the electrocardiograms did not have sufficient quality. After the removal of these six participants, the sample was distributed by the different conditions as follows:

- Audiovisual: 12 participants;
- Audiovisual + smell: 10 participants;
- Audiovisual + heat: 13 participants;
- Audiovisual + weight: 13 participants;
- Audiovisual + PPE: 11 participants.

Results from the Kruskal-Wallis H test, used to compare the distributions of the HRV parameters between conditions in the VE, showed significant differences in AVNN and pNN20 parameters and indicative differences in RMSSD and LF / HF parameters.

TABLE II. KRUSKAL-WALLIS H TEST RESULTS FOR COMPARING HRV PARAMETERS BETWEEN CONDITIONS.

Parameter	$\chi 2(4)$	p
AVNN	11.88	.018
SDNN	3.38	.428
RMSSD	7.80	.099
pNN20	10.44	.034
LF / HF	8.03	.091

Results from the pairwise comparisons, used to identify where significant differences lied, showed a significant difference between the audiovisual with PPE and the audiovisual with smell conditions in the AVNN parameter, a significant difference between the audiovisual with PPE and the audiovisual condition in the pNN20 parameter, and an indicative difference in the same parameter between the audiovisual with PPE and audiovisual with smell conditions.

TABLE III. PAIRWISE COMPARISONS RESULT FOR COMPARING AVNN AND PNN20 PARAMETERS BETWEEN CONDITIONS.

Comparison Sample 1 – Sample 2	AVNN		pNN20	
	Test statistic	*Adj. p*	*Test statistic*	*Adj. p*
PPE - Weight	9.76	1	11.46	1
PPE - Temperature	15.45	.281	12.88	.735
PPE - Control	15.66	.290	19.77	.050
PPE - Smell	24.61	.010	20.70	.058
Weight - Temperature	5.69	1	1.37	1
Weight - Control	5.90	1	8.31	1
Weight - Smell	14.85	.398	9.24	1
Temperature - Control	.21	1	-6.94	1
Temperature - Smell	9.16	1	-7.87	1
Control - Smell	-8.95	1	.93	1

The mean ranks of AVNN and pNN20 parameters between conditions during the VE showed lower values in the audiovisual with smell condition and higher values on the audiovisual with the PPE condition.

TABLE IV. MEAN RANKS OF AVNN AND PNN20 PARAMETERS.

Condition	Mean ranks AVNN	Mean ranks pNN20
Audiovisual	32.75	29.83
Smell	41.70	37.70
Temperature	32.54	36.77
Weight	26.85	28.46
PPE	17.09	17.00

Results from the Wilcoxon signed-ranks tests, used to compare HRV parameters between the baseline and virtual exercise moments of the experiment, showed significant differences in the AVNN and pNN20 parameters.

TABLE V. WILCOXON SIGNED-RANKS TESTS RESULTS ON THE COMPARISON OF HRV PARAMETERS BETWEEN THE BASELINE AND VIRTUAL EXERCISE (* SIGNIFICANT).

Parameter	Test statistic (z)	p
AVNN	-3.47	.001*
SDNN	1.36	.174
RMSSD	1.03	.305
pNN20	-3.78	<.001*
LF / HF	-1.12	.264

Results from the Kruskal-Wallis H test, used to compare the distributions of fatigue and stress, measured subjectively through questionnaires, showed significant differences between conditions in the VAS Fatigue 3 (fatigue measured after the virtual exercise).

TABLE VI. KRUSKAL-WALLIS H TEST RESULTS FOR COMPARING STRESS AND FATIGUE, MEASURED SUBJECTIVELY, BETWEEN CONDITIONS.

Instrument	$\chi 2(4)$	p
PSS	6.46	.168
CIS	7.13	.129
VAS Fatigue 1	4.37	.359
VAS Fatigue 2	2.14	.711
VAS Fatigue 3	11.40	.022
VAS Stress 1	6.77	.148
VAS Stress 2	5.80	.214
VAS Stress 3	8.03	.090

Results from the pairwise comparisons, used to identify where significant differences lied, only showed an indicative difference between the audiovisual with smell and the audiovisual with PPE conditions in the VAS Fatigue 3 variable (Test statistic = -20.483, Adj. p value = .067).

Lastly, the mean ranks of the VAS Fatigue 3 variable showed that the lowest values were shown in the audiovisual with the smell group (19.86), followed by the audiovisual (24.79), audiovisual with weight (36.75), audiovisual with temperature (37.50), and finally, with the highest values, the audiovisual with the PPE group (40.35).

V. DISCUSSION

The main goal of this work was to study the impact that different stimuli have on the physiological response of users during a firefighter training VE.

The results of the Kruskal-Wallis H test, used to compare the distributions of HRV parameters between conditions, revealed a significant difference between conditions in the AVNN and pNN20 parameters. The results of the pairwise comparisons and mean ranks showed that, in both parameters, the values were higher in the smell condition and more reduced in the PPE condition. Given that the tendency of the AVNN and pNN20 parameters is to reduce under stress [5], what the results seem to suggest is that a lower level of stress was obtained in the audiovisual and audiovisual with smell conditions, and that a higher level of stress was obtained in the audiovisual with PPE condition. Bearing in mind the goal of this study, the results suggest the use of a firefighter's PPE as a relevant stimulus to cause a stress response in the user.

Regarding the Wilcoxon signed-ranks tests, used to compare the values of the HRV parameters between the two phases of the experiment, the results showed a significant increase from the baseline phase to the virtual phase again in the AVNN and pNN20 parameters, thus suggesting that the VE was able to generate a physiological activation in the participant and that the parameters AVNN and pNN20 can be used to monitor this reaction. This result is not consistent with that of Jang et al. [9] since the LF / HF parameter failed to show differences between the phases of the experience. However, it is consistent with Jang et al. [9] and other studies [10]–[12] in the sense that the participant's cardiac variability can be used to monitor the user's response to different phases of an experiment.

In addition to HRV, subjective measures in the form of questionnaires were applied to obtain the participants' perception of stress and fatigue. The PSS and CIS questionnaires were applied in order to measure the perception of stress and fatigue, correspondingly, in a medium / long time span. VAS, on the other hand, was applied to measure the perception of stress and fatigue at the instant, having been completed at the beginning of the experiment, before the virtual exercise and after the virtual exercise (VAS 1, 2 and 3, correspondingly). The results of the Wilcoxon signed-ranks tests, used to compare stress and fatigue between conditions, showed that the perception of stress and fatigue was similar between conditions at all times of assessment except for VAS fatigue 3, that is, in fatigue after the virtual exercise. Obtaining a non-significant result in PSS and CIS is positive because it shows that the perception of stress and fatigue, measured in this case with an emphasis on a medium / long time span, was similar among participants of different conditions. As for the result obtained in VAS fatigue 3, this indicates that there was a significant difference in perception of fatigue after performing the virtual exercise. To identify where the differences lied, pairwise comparisons were performed, applying the Bonferroni correction for multiple comparisons. The results of these revealed an indicative difference (p =

.067) in the comparison of audiovisual with smell and audiovisual with PPE conditions, with the fatigue being lower in the audiovisual with smell condition and higher in the audiovisual with PPE condition. This result is consistent with the analysis of HRV, where the stress level indicated to be lower in the audiovisual and audiovisual with smell conditions and higher in the audiovisual with PPE condition. However, despite being coherent, this can be seen as a factor that limits the validity of the result obtained in HRV, since it indicates the presence of physical stress. Despite this, the authors believe that the stress exhibited in the analysis of HRV was not only due to physical stress because participants in the audiovisual with weight condition carried exactly the same weight and because during almost the entire duration of the exercise the user remained seated, where the weight of the SCBA was supported by the ground itself.

VI. Conclusions and Future Work

The main goal of this work was to study the impact that different stimuli have on participants' HRV during a VE designed to train firefighters.

The results of the analysis of HRV suggest that, of the four stimuli used, the one that seems to have the greatest influence on a stress response is the use of a firefighter's PPE. The results support the use of the HRV parameters AVNN and pNN20 as a way to monitor a user's response to a training VE. Regarding the analysis of HRV between two moments of the experience, namely baseline and virtual exercise, the results are consistent with the existing literature, indicating that HRV can be used to distinguish different phases of an experiment.

As future work, the authors plan to conduct further tests to study the impact of additional individual stimuli, as well as the impact combined stimuli, on user's cardiac response.

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