Exploring eye-blink startle response as a physiological measure for affective computing

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***Abstract*—In affective computing, detection of stress and negative emotions with physiological measures typically employs well-known signals such as skin conductance, activity of cheeks and forehead muscles, heart rate or heart rate variability. However, psychophysiology experiments in the literature offer additional measures (such as eye-blink startle response) not yet exploited in affective computing applications. Procedures to elicit eye-blink startle responses are often based on acoustic stimuli, in particular short bursts of intense white noise. Unfortunately, following this approach in affective computing applications would not be natural, because the artificial white noise bursts would be intrusive sounds unrelated to the user experience. They would thus distract the user from the meaningful events in the application and user's (conscious or unconscious) attempts to relate those events to the artificial stimuli would be unsuccessful and frustrating, making the stimuli detrimental to the user experience. Our research aims at exploring if sounds that have a meaningful relation with the events in the application could be used as an alternative to white noise bursts. The study we present in this paper compares physiological responses of users of a 3D virtual environment in two conditions (measurement of eye-blink startle response to white noise or to an alternative sound that is related to the experience), showing that the two types of acoustic stimuli produce a similar intensity of startle response. This result suggests that eye-blink startle response could be used in natural ways to extend the set of physiological measures employed in affective computing.**

Keywords-affective computing; eye-blink; startle response; EMG; white noise; natural noise

I. Introduction

In affective computing, detection of stress and negative emotions with physiological signals is typically based on a relatively small set of measures. Electrodermal activity (EDA) [1][2][3][4][5], muscle activity (EMG) of *corrugators supercilii*, *zygomaticus major*, or *trapezius* muscles [1][5][6], heart rate and heart rate variability (HR and HRV) [2][4][5][6], are employed very often. In a few cases, skin temperature [4], respiration [1][6], and pupillometry [7] have been considered. However, the psychophysiology literature offers additional measures (such as *eye-blink startle response*), whose potential has not yet been exploited in affective computing applications.

Eye-blink startle response has been successfully used in psychophysiology and biological psychiatry to assess the intensity of negative emotions such as contextual fear, and contextual and anticipatory anxiety (e.g., [8][9][10]), or more generally emotional valence (e.g., [10][11][12]). A few studies have employed it also in measuring immersion (e.g., [13][14]).

Eye-blink is measured by analyzing the peak in the surface EMG signal recorded beneath the eye and elicited by an acoustic, visual, or mechanical stimulation. In most studies, startle responses are elicited by acoustic stimuli, in particular short bursts of intense white noise at 100-110 dB. Unfortunately, following this approach in affective computing applications would not be natural, because the artificial white noise bursts would be intrusive sounds unrelated to the user experience. They would thus distract the user from the meaningful events in the application and users' (conscious or unconscious) attempts to interpret them or to associate the bursts to a particular object or event would be unsuccessful and frustrating. As a result, those stimuli would be detrimental to the user experience.

The goal of our research is to assess if more realistic and natural acoustic stimuli (more specifically, sounds that can be easily recognized because they naturally presents themselves in real-world events, and can be easily interpreted in the context of the application because they have a meaningful relation with the visual cues presented by the application itself) elicit comparable eye-blink startle responses compared to traditional white noise stimuli. This would open up the possibility to extend in a natural way the set of physiological measures employed in affective computing with eye-blink startle response.

The experiment we present in this paper compared the intensity of participants' eye-blink startle responses to two different acoustic stimuli, an intense burst of white noise typically used in the psychophysiology literature, and a sound with similar characteristics (in terms of duration and intensity) that is produced in the real-world by explosions. These two stimuli were presented to participants while they used a 3D virtual environment (VE) built with a game engine. The VE reproduces a school building during a fire emergency, a virtual experience to which explosion sounds may naturally belong.

The paper is organized as follows. In Section II we introduce the eye-blink startle response and describe how it is being used in the literature. The two acoustic startle stimuli as well as the VE employed in the present study are discussed in Sections III and IV. Sections V and VI describe in detail the experiment and its results, while Section VII critically discusses the results and present the future work.

II. Related Work

Startle response is a complex of bodily reactions to a strong, rapid, and unexpected stimulus [15]. In particular, eye-blink startle response is the fastest and more stable component of the startle response [16]. Currently, surface EMG is the most frequently used measure in human eye-blink startle response research [17]. EMG recording electrodes are typically placed over the *orbicularis oculi* muscle, beneath the left or right eye [17].

Startle responses are generally elicited through acoustic stimulation [12][18][19][20][21][22][23]. As reported in [17], a startle response can also be elicited through visual stimuli, such as light flashes [24] or mechanical stimuli (taps or air puffs on skin) [25], which research shows can be used as alternatives to white noise stimuli [26]. The most common startle stimulus is a short (about 50 ms) burst of broadband (white) noise with intensities in the range of 100 dB or more [17]. The intensity of the sound is typically weighted using the *A* weight filter which approximates the human ear's response to sound. The stimuli are generally presented at pseudo-random instants, with intervals of about 15-30 s between two consecutive stimuli (e.g., [12][23]). The EMG onset caused by the stimulus can be observed in the 21-150 ms window after the stimulus itself; however, the use of signal filtering, smoothing or integration can change the latency of the signal onset [17].

The intensity of the startle response has been successfully correlated with fear, general anxiety, anticipatory anxiety [1][21][23], i.e., anxiety elicited by the anticipation of a threat. Fear context conditioning has also been the focus of physiological studies employing eye-blink startle response [10][27][28]. Some studies have related the intensity of the startle response to worry [22], i.e., a chain of thoughts and images, negatively affect laden and relatively uncontrollable, that promotes mental attempts to avoid anticipation of potential threats [29].

As a measure of people reactions to viewing positively- and negatively-valenced pictures, the intensity of eye-blink startle response has been positively correlated to the unpleasantness of the picture [18][22][23][24][30]. Most of these studies have employed pictures from the International Affective Picture System (IAPS) [31], which provides normative ratings of emotion (pleasure, arousal, dominance) for a set of color photographs.

It is interesting to note that recent psychophysiological studies resorted to VEs as a source of visual stimuli, and provided further support for the validity of eye-blink startle response as a measure of negatively-valenced emotions. For example, researchers have used dark immersive VEs to elicit fear and were able to measure the effect with eye-blink startle response [19][20]. In [12], authors evaluated the effects of darkness while users were actively driving or sitting in the passenger seat of a virtual car that was travelling through a virtual tunnel characterized by the presence or the absence of darkness. Eye-blink startle responses were able to discern the anxiety level generated by the two different VEs when the user was passively immersed in the virtual driving task. Mühlberger, Bülthoff, Wiedermann, and Pauli [21] employed a virtual tunnel VE to assess the effect of tunnel phobia on startle response, observing again that eye-blink startle response is a good measure to assess fear- and anxiety-related emotional states. Immersive and realistic VEs were employed by Cornwell, Johnson, Berardi, and Grillon [11], who correlated the startle potentiation with the anxiety elicited by a socially anxious virtual experience (standing center-stage in front of an audience to anticipate giving a speech) and a less anxious one (an empty room).

Eye-blink startle response was used by some researchers also as a measure of immersion in VEs [13][14], and a possible source of benchmarking metrics for the efficacy of VEs in therapeutic and training applications [32]. The use of devices like *head-mounted displays* (HMDs) to increase immersion in VEs seems to have a significant effect on the potentiation of eye-blink startle responses [33].

III. Startle Stimuli

The white noise stimulus we use in the present study replicates the stimulus employed in [12], which follows the guidelines defined in [17]. It is a 40 ms burst of 103 dB (A) intensity with instantaneous rise time, no decay and no release time, and a flat power density over the entire audible frequency spectrum (20-20000 Hz).

The chosen natural sound is inevitably characterized by some differences with respect to the white noise stimulus. It is the sound of an explosion that reaches the same intensity of the white noise stimulus but is longer (600 ms). It is characterized by a brief rise time (about 5 ms), no decay time, a sustain time of about 200 ms, and a release time of about 400 ms. The bandwidth is in the audible range, with almost all power spectral density in the 20-16000 Hz range. The maximum intensity is in the 20-500 Hz band (with a peak in the first octave); intensity decreases linearly by 1 dB about every 1000 Hz in the 500-6000 Hz range, and by 1 dB about every 500 Hz in the 6000-16000 Hz range.

To choose the natural startle stimulus, we first collected ten sounds of explosions and/or objects crashing. This initial choice was motivated by the fact that the virtual experience reproduced by the VE was a fire emergency, a situation in which the occurrence of that kind of sounds is meaningful and appropriate. Among them, we selected those with shorter rise time and shorter total duration. Among the three selected sounds, we chose the one that sounded easiest to recognize (an explosion sound).

Figure 1. A screenshot of the VE employed in the study showing a corridor full of smoke and corpses lying on the floor.

Startle stimuli (as well as any other sound in the VE) were presented to the user through a setup composed by two loudspeakers, placed on the sides of the computer monitor and connected to a 120 W RMS amplifier. We preferred this setup to headphones to avoid interferences with EMG physiological sensors as suggested by Blumenthal et al. [17].

To gurantee that the intensity of the explosion sound and the white noise were the same, we measured then during the audio system set-up with a Brüel & Kjær sound level meter, placed at 1.1 m height from the floor and 1.5 m distance from the screen. The chair on which participants sat was placed in such a way that their head was located in the same position where the intensity of sound had been measured, and they could not move the chair during the task. We also measured the background sound intensity of the VE, which was designed to remain inside the 65-75 dB (A) range during the entire experience. This is a common intensity range for background sound in startle response studies [17].

IV. THE CONSIDERED VIRTUAL ENVIRONMENT

In our study, we employed a VE that reproduces a multi-floor school building in which each floor is made by classrooms and corridors. In the virtual experience, the user starts at the top floor, inside an empty classroom. To move inside the VE, (s)he employs a Nintendo Nunchuck controller, equipped with a joystick and two buttons. By moving the joystick forward or backwards, the user walks respectively forward and backward in the VE; by moving the joystick to the left or to the right, the user rotates his body respectively counterclockwise or clockwise in the VE. The larger of the two buttons is used to open the doors. The user is required to evacuate the building by following a series of green emergency exit signs placed over the doors and the walls to lead her to the ground floor. Only the doors belonging to the exit path could be opened, all other doors in the building were locked.

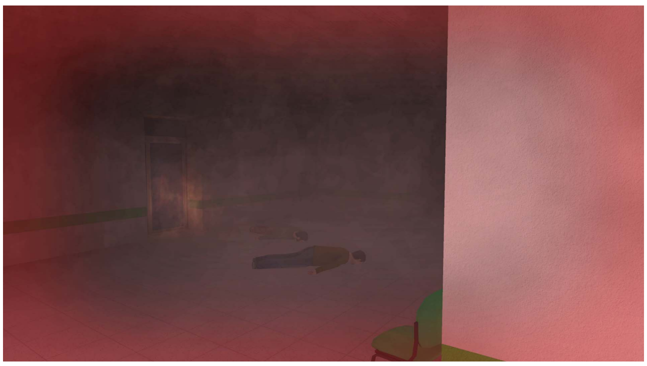

Figure 2. A screenshot of the VE showing the red aura.

The VE reproduces a fire emergency: a constant amount of smoke fills the different areas of the environment as shown in Fig. 1, and there are occasional corpses of victims (which the user cannot interact with) lying on the floor along the path. The audio background is made of screaming people, ambulance sirens, and fire alarm sounds; the user can also hear her “virtual” breath and heartbeat. At the beginning of the virtual experience, the user is healthy, and is able to virtually run inside the VE. However, as the experience progresses, visual and auditory cues simulate her degrading health conditions caused by smoke inhalation. More specifically, she can hear herself breathing with more and more difficulty, the breathing sound becomes more and more intense; the frequency and the intensity of the played heartbeat increases; and a red aura (Fig. 2) flashes in synch with heartbeat, progressively increasing in size to reduce the user’s field of view. Walking speed slows down as time passes, and at the end of the virtual experience (3 minutes after the start) the user is almost unable to move.

V. EXPERIMENTAL EVALUATION

The experiment followed a between-subjects design, with *startle stimulus* (*white noise* or *explosion sound*) as the independent variable and measured eye-blink response magnitude.

A. Participants

The evaluation involved a sample of 36 participants (21 M, 15 F) recruited among students. Age ranged between 16 and 35 (M = 23.89; SD = 3.34). Only one participant was a minor, and parents’ approval was obtained in her case. A demographic questionnaire was employed to gather information about participants’ age, gender, and video game usage. Video game usage in the sample was as follows: 4 participants never play video games; 7 participants play less than once a month; 2 participants about once a month; 8 participants more than once a month; 8 participants more than once a week; 6 participants about 1-3 hours a day; one participant more than 3 hours a day. Usage of 3D video games with realistic graphics was as follows: 11 participants never play them; 8 participants play less than once a month; 2 participants about once a month; 5 participants more than once a month; 7 participants more than once a week; one participant every day for less than one hour; 2 participants 1-3 hours a day.

The results of the demographic questionnaire were used to assign participants to the two levels of the startle stimulus variable in such a way that the averages of the four demographic indexes (age, gender, video game usage, realistic 3D video game usage) were as similar as possible for the two

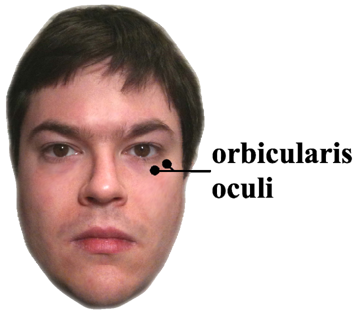

Figure 3. The two black dots pinpoint the location of EMG electrodes for eye-blink startle response measures.

groups. More specifically, mean age was 24.11 (SD = 4.14) for the white noise group and 23.67 (SD = 2.38) for the explosion sound group; mean video game usage on the employed scale (0: never; 1; less than once a month; 2: about once a month; 3: more than once a month; 4: more than once a week; 5: every day, for less than 1 hour; 6: every day, for about 1-3 hours; 7: every day, for more than 3 hours) was 2.94 (SD = 1.76) and 3.16 (SD = 2.31) respectively; mean usage of 3D video games with realistic graphics was 1.89 (SD = 1.81) and 2.11 (SD = 2.03) respectively.

B. *Materials*

The two VEs were run on a Mac Pro (with two quad-core processors at 2.8 GHz; 4 GB RAM; NVidia 8800 GT graphic card with 512 MB of dedicated memory) on a 30'' LCD monitor at WQXGA resolution (2560 × 1600 pixels).

To record participants' eye-blink startle response data, we employed an EMG sensor with two disposable pre-gelled electrodes attached at a constant inter-electrode distance of 2 cm over the orbicularis oculi muscle, beneath the left eye, following the electrode placement recommended by [34] (Fig. 3). The signal, recorded using a ProComp Infiniti encoder, was sampled at 1024 Hz. Following the guidelines by Blumenthal [17], a band-pass filter in the 28-500 Hz range was first applied, then the filtered signal was rectified with a moving window and finally smoothed with a variable-weight FIR filter with a low-pass cutoff frequency of 40 Hz.

C. *Procedure*

Participants were verbally instructed about the task, and informed about the presence of intense but very short noises (the startle stimuli) during the experience. They were also clearly informed that all the experimental data was going to be collected and analyzed anonymously for research purposes. The white noise and the explosion sound were presented to them two times each. Then, participants were asked if they agreed to participate to the experiment. All of them consented to participate and none of them found the stimuli intensity intolerable. After they filled the demographic questionnaire, participants were seated and the skin under their left eye was cleaned using a pad of cotton wool and alcohol, then the EMG sensor was applied.

Then, they were asked to relax for a minute while watching a video with relaxing images and music, so that physiological parameters could reach a rest state. Finally, they carried out the task, which lasted 3 minutes.

During the task, six startle stimuli were delivered to participants. The first stimulus was administered 29 s ± 5 s after the start of the experience (the value in the ± 5 range was randomly chosen). Similarly, the distance between each pair of subsequent stimuli was 29 s ± 5 s, with the random numbers chosen in such a way that the mean of the five temporal distances between two consecutive stimuli was 29 s. The purpose of this pseudo-randomization of the startle stimuli timing is to prevent learning effects.

Finally, participants were debriefed about the experiment and thanked for their participation.

VI. Data Analysis and Results

A. *Data reduction and analysis*

To gather eye-blink startle response data, we followed a procedure similar to the one described in [12]. We analyzed manually the filtered EMG data, and identified the EMG value of the signal peak in a 20-500 ms window after the stimulus. The width of this time window has been set to preemptively take into account any possible latency caused by EMG signal filtering, as recommended in [17]. The window can also take into account possible latency that might be introduced by the slightly longer duration and rise time of the employed explosion sound startle stimuli. An example of eye-blink startle response (filtered as described in the Materials section) is provided in Fig. 4.

The baseline value for each startle response was calculated as the mean EMG value in the 0-20 ms time interval after the startle stimulus presentation. The EMG signal was visually examined to detect possible situations in which artifacts might have negatively affected the assessment of a startle response. This may happen, for example, if the user closes her eyes during the startle stimulus presentation and, as a result, the baseline for determining the startle magnitude becomes unreliable. In these (relatively rare) cases, the affected startle response has to be discarded. To obtain the magnitude for a startle response, the relative baseline value was subtracted from the EMG value of the peak.

One participant in the white noise group had to be

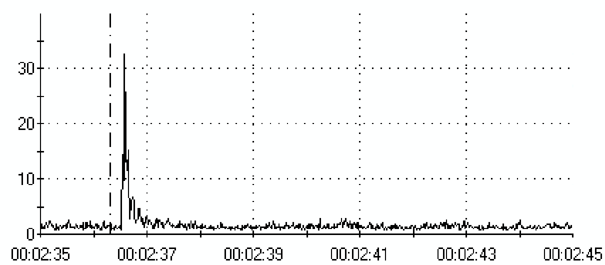

Figure 4. Filtered EMG signal showing an eye-blink startle response to a stimulus presented in correspondence to the dot-dashed vertical line.

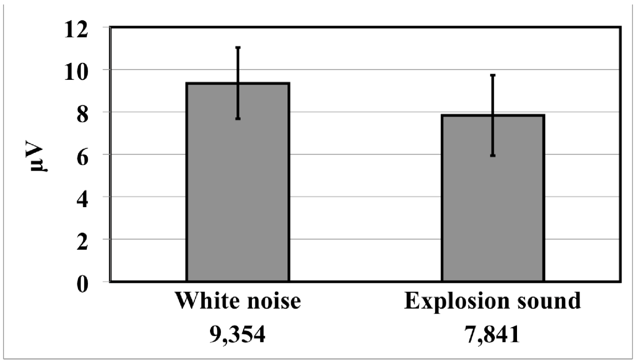

Figure 5. Mean magnitude of eye-blink startle responses to the white noise and the explosion sound. Error bars indicate standard error of the mean.

excluded because her EMG data was corrupted by a malfunctioning or improperly applied disposable electrode.

For each participant, we calculated the mean EMG value of the six startle responses. We excluded outliers by using the method recommended in [17]: participants with a mean EMG value larger than 3SD from the mean EMG value of the group they belong to were removed from the data set. As a result, we excluded two participants from the analysis, one for each group.

B. Results

Before analyzing the data set with a two-tailed unpaired t-test, we assessed data normality (a prerequisite for the t-test) using the Shapiro-Wilk test [35]. The results showed that the data did not follow a Gaussian distribution; therefore, we applied a log-transformation, as suggested in [36], to normalize the data.

The t-test performed on the transformed data revealed no significant differences ($t(31) = 1.15$, $p = 0.26$) between the white noise group ($M = 9.35$, $SD = 6.70$) and the explosion sound group ($M = 7.84$, $SD = 7.84$). The untransformed mean values are shown in Fig. 5.

VII. Discussion and Conclusions

In the present study, we compared eye-blink startle responses elicited by a traditional white noise startle stimulus and a more natural explosion sound of equal intensity. Participants were immersed in a VE reproducing a school building during a fire emergency, a virtual experience to which explosion sounds may naturally belong.

The results of the study show that: (i) the explosion sound is able to elicit an eye-blink startle response, and (ii) the magnitude of the response is close to the one elicited by white noise, and the small difference is not statistically significant. This indicates that the rise time of the explosion sound (one of the parameters of acoustic startle stimuli that seems to play the most important role in startle potentiation [17]) was short enough to elicit an intense startle response. Indeed, one of the factors that led us to choose that particular explosion sound was its short rise time (about 5 ms). Similarly, the longer duration of the natural noise stimulus did not result in a significant negative impact on the magnitude of the startle response. While the white noise is shorter and maintains its intensity for the entire duration of the stimuli, the explosion sound is longer but the decay described in the Startle Stimuli section actually reduced the time during which it is intense, attenuating the possible negative effects of the longer duration. In any case, we could not find in the literature studies comparing the effects of different stimulus durations. A 40 or 50 ms duration is typically employed and sufficient for startle elicitation. Longer white noise stimuli are probably not employed because, while not unsafe, they may be too uncomfortable for participants [17].

The observed results are promising with respect to the possible use of more natural startle stimuli and encourage further exploration with different realistic and recognizable acoustic startle stimuli in place of white noise. The ultimate goal would be to extend in a natural way the set of physiological measures employed in affective computing with eye-blink startle response, which can be used to assess the intensity of users' negative emotions such as anxiety (e.g., [8][9][10]), as well as sense of presence in the VE (e.g., [13][14]). As shown by some studies (e.g., [7]), the use of multiple physiological sensors may help to improve the accuracy of automatic stress detection.

Sounds like explosions can naturally present themselves in real-world events, and thus can be easily interpreted in the context of a realistic VE, because they have a meaningful relation with the visual cues presented by the virtual experience. The presentation of a natural acoustic stimulus, unlike white noise, can therefore become an integral part of the user experience, and may even increase the immersion of the user instead of potentially hindering it. It is important, however, to accurately select the right natural sound for the chosen VE, otherwise the stimuli, albeit natural, would be as intrusive and distracting as white noise: for example, consider the explosion sound in a relaxing virtual experience inside a forest. In searching for a suitable natural stimuli, one must balance: (i) the realism and familiarity of the sound (i.e., how easily it can be recognized and interpreted as an element of the VE), and (ii) its effectiveness in eliciting a startle response of adequate intensity.

For these reasons, in future studies, we will evaluate different natural noises to create a collection of realistic startle stimuli that can be easily associated to virtual objects and events: besides explosions and crashes, one can consider sounds such as human or animal shouts, car horns, telephone rings, and so on. A large number of tested stimuli can extend the number of applications in which eye-blink startle response could be naturally applied.

Finally, we will extend our study, by evaluating not only the magnitude of the responses elicited by different startle stimuli, but also the possible effects of different virtual experiences, focusing in particular on comparisons between stressful and non-stressful VEs (e.g., [12][33]). The goal is to assess if natural startle stimuli, besides being able to elicit startle responses that are comparable to white noise as we have seen in this paper, have a different discriminating power in analyzing the valence of emotions.

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