Temporal characteristics of skin conductance and subjective intensity in response to unpleasant audio-visual and vibrotactile stimuli

Ibuki Tara, Shogo Okamoto, Yasuhiro Akiyama, and Yoji Yamada

Abstract—In this study, we measured and modeled the changes in physiological and subjective signals when the participants were subjected to unpleasant stimuli, such as a horror movie and vibrotactile stimuli to the upper body. We measured skin conductance as a physiological value and grip force, which was adjusted to express the level of subjective unpleasantness. We then modeled the skin conductance and grip force as second-order lag systems and computed their characteristic parameters. The damping ratios for skin conductance and grip force were slightly greater than 1.0, and the natural frequency of the grip force was greater than that of the skin conductance. The response delay of the skin conductance was longer than that of grip force by approximately 1 s. In terms of the behavior of the skin conductance, the differences among individuals and the types of stimuli were almost null from the stimulus onset to the peak, but after the peak, the differences were substantial. The temporal changes in the subjective intensity were significantly different among participants. These characteristics are useful for designing emotionally responsive systems that use emotional signals to adapt their behavior.

I. INTRODUCTION

The demand for human-system cooperation technology, such as collaborative and communication robots [1], [2] has been increasing. Estimation of emotional states is a key component of such technologies. Physiological indexes such as heart rate, skin conductance [3], and facial images [4] are used to estimate the user's emotional states. Estimated emotional states are used by robotic and information systems that behave or react in response to the emotional states of the user. Alternatively, systems exist that use emotional states that are subjectively reported by users. Hence, both physiological and subjective indices are available for human-system cooperation. Emotional states change temporally, and we need to understand their dynamic characteristics to design emotionally responsive systems. Many studies measured and modeled temporal responses of physiological signals [5], [6]. However, few studies have compared the temporal characteristics of physiological and subjective responses to the same stimuli.

This research focused on the dynamics of emotional state signals. We measured and modeled the temporal changes in the skin conductance and subjectively reported emotional states in response to unpleasant stimuli that evoke fright or warning, and specified their temporal characteristics. We used audio-visual stimuli, such as a horror video and vibrotactile stimuli, to trigger emotional changes. Vibrotactile stimuli tend to provoke unpleasant feelings and are often used as warning stimuli [7]. Nonetheless, they can be linked to positive emotions [8], [9], and they lead to a variety of applications. We used skin conductance for physiological measurement, which is suitable as an interface for human-machine systems because of its quick response to stimuli and measurement accessibility. Further, the time-intensity method [10] was used to record subjectively reported emotional states.

II. METHOD

A. Unpleasant audio-visual and vibrotactile stimuli

We used a horror video [11] and vibrotactile stimuli. The video was approximately three minutes long in which a man found a polaroid camera and took photos of his room, then he noticed a devil in the photo, and finally, a real devil appeared and assaulted him.

We used vibrotactile stimuli to induce unpleasant emotions. As described in Section II C, vibrators were attached to the eight points on the trunk of the participant and generated a vibration of 70 Hz with a constant amplitude for 7 s.

B. Measurement of emotional responses

We measured the temporal evolution of skin conductance as a physiological index. Skin conductance is calculated from the voltage difference between two electrodes attached to the skin surface. Sweating increases this value.

We used the time-intensity method [10] for recording subjective emotional state. In this method, the participant reports the transient feeling level, typically by using a joystick or visual-analog scale. In our study, a grip force was used to express the intensity because the gripping task did not incur any visual loads. The participant was instructed to adjust the gripping force according to his/her transient unpleasantness.

C. Apparatus

A video player, vibrators, and the measurement of skin conductance and grip force were controlled or monitored by a single microcomputer (MBED, ARM Ltd., England) to share the same temporal base. A digital signage controller (BS/HD220, BrightSign, CA) received an ignition command from the microcomputer, to play audio-visual content. Voicecoil motors (VP408, Acouve Lab., Japan) were attached to the chest, abdomen, waist, and shoulders through a vest. The vest was adjusted such that the voicecoil motors were firmly in contact with the wearer’s body. We used Bitalino (BPK160616, Plux-Wireless Biosignals, Portugal) to measure skin conductance. Pairs of electrodes were attached to the palms of each participant after the palms were cleaned.

This study was in part supported by MEXT Kakenhi (20H04263). All are with the Department of Mechanical Systems Engineering, Nagoya University, Japan.
Fig. 1. Vibrotactile vest with eight high-fidelity voicecoil motors.

Fig. 2. Four types of parameters were measured for the skin conductance and grip force: latency, rising time, half recovery time, and recovery time constant.

To record the subjective intensity of feeling, we used a home-made grip dynamometer based on a strain-gauge-typed loadcell (1040-0020-F000-RS, Tedea-Huntleigh, Israel). The participant grasped the dynamometer in his/her dominant hand.

D. Experimental tasks

We conducted two experiments to measure human responses to audio-visual and vibrotactile stimuli. Four university students who were unaware of the study objectives participated in two tasks.

In one experiment, the participants wore the vibrotactile vest and experienced vibrotactile stimuli in a resting state with eyes closed. The change in the skin conductance was measured. We did not inform the participants of the timing to start the vibrotactile stimuli. This measurement was conducted one time for each individual.

In another experiment, the participant watched a three-minute horror video, and the subjective intensity of unpleasantness was measured by the time-intensity method using a grip dynamometer. During this task, the participant’s skin conductance was also recorded. The audio-visual stimulus task was performed only once by each participant.

III. Analysis

As shown in Fig. 2, four types of parameters [10], [12] were computed from the acquired time-series responses. They include

- Latency: The time between the stimulus onset and the time for the skin conductance or grip force to start rising.
- Rising time: The time between the point at which the skin conductance or grip force starts rising and the time at which its peak value is recorded.
- Half-recovery time: The time between the peak and the point at which the skin conductance or grip force recovers to the half peak.
- Recovery time constant: The time between the peak and the point at which the skin conductance or grip force recovers to 37% of the peak.

We selected two scenes that could strongly induce fright and for which the beginning of the horror scenes could be clearly defined. There were some sections where the half-recovery time or recovery time constant of the skin conductance could not be calculated because the value converged to more than 50% or 37% of the peak amplitude. Hence, we could not acquire a sufficient number of samples in the experiment of vibrotactile stimuli, and we excluded the half-recovery and recovery time constants from the analysis.

Furthermore, we computed two parameters describing the dynamics of systems. The response of skin conductance was modeled as the free vibration of an overdamped second-order lag system [5]. There is no standard model for the time-intensity signals; hence, we also applied the second-order lag system to the grip force to compare their temporal characteristics. For the model construction, the response signals after the rising points were used. The model estimation was performed based on the least-squares method. The model formula was,

$$x(t) = A \left( e^{-\lambda_1 t} - e^{-\lambda_2 t} \right),$$

where $A$ determines the amplitude of the skin conductance or grip force changes, and $\lambda_1$ and $\lambda_2$ are real positive values to determine their response profiles. The second-order lag elements were calculated using $\lambda_1$ and $\lambda_2$ as follows:

$$\zeta = \frac{\lambda_1 + \lambda_2}{2\sqrt{\lambda_1 \lambda_2}},$$

$$\omega_n = \sqrt{\frac{\lambda_1 \lambda_2}.}$$

We excluded outlier profiles that included shapes that did not fit the curve of second-order lag systems and at least one parameter that was out of the two times standard deviations.

IV. Results

Fig. 3 shows an example of the skin conductance change after experiencing the vibrotactile stimuli. Fig. 4 shows changes in the skin conductance and grip force after experiencing the audio-visual stimuli, i.e., a horror scene. Fig. 5 shows the regression curves for the second-order lag systems. Table I summarizes the mean and standard deviation of the parameters among the four participants.

For skin conductance, the latency and rising time were approximately 1.4 s and 1.9 s, respectively, irrespective of the type of stimuli. The differences among the individuals...
TABLE I
MEAN AND STANDARD DEVIATION OF THE RESPONSE PARAMETERS

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<th>Audio-visual stimuli</th>
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<th>Vorbroctile stimuli</th>
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<td>Latency</td>
<td>1.42 ± 0.27 s</td>
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<td>1.43 ± 0.02 s</td>
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<td>Rising time</td>
<td>1.87 ± 0.27 s</td>
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<td>1.93 ± 0.26 s</td>
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<td>Half recovery time</td>
<td>3.81 ± 3.61 s</td>
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<td>Recovery time constant</td>
<td>4.15 ± 2.08 s</td>
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<td>0.45 ± 0.14</td>
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<td>0.65 ± 0.11</td>
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<td>0.85 ± 0.10</td>
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<td>1.03 ± 0.03</td>
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<td>1.12 ± 0.03</td>
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<td></td>
<td>0.54 ± 0.11 rad/s</td>
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<td>0.53 ± 0.09 rad/s</td>
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and scenes in the video were negligible. Conversely, the half-recovery and recovery time constants varied significantly among the participants and the type of stimuli. These tendencies of the response parameters are in accordance with the general skin conductance characteristics [12], where the latency is typically between 1 and 2, and the rising time is between 1 and 3.

The latency and rising time of subjective intensity were shorter than those of the skin conductance by approximately 1 s, and on average, the subjective intensity began to rise at 0.23 s after the stimulus onset, whereas the skin conductance began to change at 1.42 s on average. The coefficients of variation, that is, the ratios of the standard deviation to the mean of grip force, tended to be larger than those for skin conductance. This is because the measured value was consciously determined by the participants in the time-intensity method, whereas the skin conductance value changed automatically. The natural frequencies, \( \omega_n \), of the grip forces were 1.56 ± 0.30 rad/s and larger than those for skin conductance (0.54 ± 0.11 rad/s), which indicates that the rising time to the peak was less for the grip force. The damping ratios of the second-order lag models for skin conductance and grip force were slightly greater than 1.0.
V. CONCLUSIONS

In this study, we measured and modeled the temporal changes in skin conductance and voluntary grip force in response to unpleasant audio-visual and vibrotactile stimuli and analyzed their characteristics. The delay in skin conductance was longer than that of the subjective intensity by approximately 1 s. The differences among the individuals and stimuli were almost null in the behavior of skin conductance from the stimulus onset to the peak, but the post-peak differences were substantial. The rising time of the grip force was substantially smaller than that of the skin conductance. Accordingly, the natural frequency of the grip force was greater than that of the skin conductance. These results collectively indicate that the grip force, as an indicator of subjective intensity of unpleasantness, changes more rapidly than skin conductance. These differences in the subjective and physiological responses to unpleasant stimuli should be reflected in the design of emotionally responsive human-machine systems. The number of participants in the experiments was small, and we could not make statistical conclusions. In the future, a larger number of participants should be involved. Furthermore, although we used the second-order lag system for modeling the subjective grip force, we need to consider the validity of this model for subjectively reported emotional intensity.

REFERENCES