Predicting Individuals' Experienced Fear From Multimodal Physiological Responses to a Fear-Inducing Stimulus

Eun-Hye Jang[1], Sangwon Byun[2], Mi-Sook Park[3], and Jin-Hun Sohn[4]

[1] Welfare & Medical ICT Research Department, Electronics and Telecommunications Research Institute (ETRI), 218 Gajeong-ro, Yuseong-gu, Daejeon, 34129, Republic of Korea

[2] Department of Electronics Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon, Republic of Korea

[3] Department of Rehabilitation Counselling, Seoul Hanyoung University, 290-42 Kyoungin-ro, Guro-gu, Seoul, 08274, Republic of Korea

[4] Department of Psychology, Brain Research Institute, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon, 34134, Republic of Korea

ABSTRACT

Emotions are experienced differently by individuals, and thus, it is important to account for individuals' experienced emotions to understand their physiological responses to emotional stimuli. The present study investigated the physiological responses to a fear-inducing stimulus and examined whether these responses can predict experienced fear. A total of 230 participants were presented with neutral and fear-inducing film clips, after which they self-rated their experienced emotions. Physiological measures (skin conductance level and response: SCL, SCR, heart rate: HR, pulse transit time: PTT, fingertip temperature: FT, and respiratory rate: RR) were recorded during the stimuli presentation. We examined the correlations between the physiological measures and the participants' experienced emotional intensity, and performed a multiple linear regression to predict fear intensity based on the physiological responses. Of the participants, 92.5% experienced the fear emotion, and the average intensity was 5.95 on a 7-point Likert scale. Compared to the neutral condition, the SCL, SCR, HR, and RR increased significantly during the fear-inducing stimulus presentation whereas FT and PTT decreased significantly. Fear intensity correlated positively with SCR and HR and negatively with SCL, FT, PTT, and RR. The multiple linear regression demonstrated that fear intensity was predicted by a combination of SCL, SCR, HR, FT, and RR. Our findings indicate that the physiological responses to experiencing fear are associated with cholinergic, sympathetic, and α-adrenergic vascular activation as well as myocardial β-sympathetic excitation, and support the use of multimodal physiological signals for quantifying emotions.

KEYWORDS

fear intensity
experienced emotion
physiological signals
autonomic responses

INTRODUCTION

Emotion recognition has been studied in affective computing and human-computer interaction (HCI) as a crucial machine capacity for effective communication (Choi et al., 2015; Park et al., 2013). Previous studies have demonstrated that emotional stimuli can elicit spontaneous reactions from the autonomic nervous system (ANS), which affects various physiological signals such as heart rate (HR), respiratory rate (RR), blood pressure (BP), skin conductance, and body temperature (Levenson, 2014). Physiological responses to emotions are relatively similar among different societies and cultures since they are mostly involuntary and resistant to deception (Drummond & Quah, 2001; Tsai et al., 2000; Tsai et al., 2002). In addition, physiological signals can be measured using noninvasive and simple methods, which are important advantages in developing emotion recognition. Therefore, physiological signals have been previously studied with the aim of recognizing human emotions based on a strong relationship between physi-

Corresponding author: Jin-Hun Sohn, Department of Psychology, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon, 34134, South Korea. E-mail: jhsohn@cnu.ac.kr; Sangwon Byun, Department of Electronics Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon, Republic of Korea. E-mail:swbyun@inu.ac.kr

ological reactions and emotional and affective states (Park et al., 2013).

Detection of the fear emotion has also been studied based on physiological signals, which can be applied to criminal investigation, intelligent surveillance systems, and treatment of anxiety disorders (Choi, et al., 2015). Fear is a withdrawal-related emotion with high arousal and negative valence that is elicited by an event appraised as threatening. This leads to an activation of the ANS and a possible fight-or-flight response. Emotion encompasses both the process of emotion elicitation and the emotional response (e.g., Scherer & Moors, 2019). As individuals respond with varying intensity to the same emotional stimulus, it is important to consider their experienced emotions to understand their corresponding physiological changes. Evaluating emotion at the individual level is important in developing user-specific HCI technologies, which benefit substantially from tracking users' emotional states.

Fear is also defined by the conscious emotional experience that occurs when an organism is threatened (LeDoux, 2014), which is closely bound to changes in bodily sensations (Pace-Schott et al., 2019). The direction of causality and the specificity of relationships between physiological responses and emotional experience have been debated ever since James (1890) proposed that subjective emotion is determined by somatic responses to stimuli. Since emotion is a multicomponent process, it is crucial to investigate it at different levels, including physiology, which complements self-reported emotional experience and behavior (Pace-Schott et al., 2019). For example, Grandjean et al. (2008) proposed the hypothesis that conscious emotional experience emerges as a function of multilevel, appraisal-driven response synchronization. Meanwhile, studies on individual differences in physiological responses to emotional stimuli have demonstrated that some people are highly responsive to self-produced cues from their own behavior (e.g., facial expressions, actions), whereas others are more responsive to situational cues from their understanding of the context (e.g., norms about situations, social pressures, Laird & Berglas, 1975; Laird & Lacasse, 2014).

Various approaches in affective sciences have been used to investigate the relationship between physiological responses and emotional experience. For example, dimensional models of emotion based on arousal and valence have been used widely to describe the experienced emotion and relate emotional intensity to physiological responses (Bradley et al., 2001; Bradley & Lang, 2000; Lang et al., 1993; Jenke & Peer, 2018). These studies have demonstrated that arousal and valence ratings are related significantly to physiological responses to emotional stimuli. Lang et al. (1993) also examined the relationship between physiological responses and emotional intensity. However, they measured intensity as the level of arousal and valence instead of the level of the experienced discrete emotion, that is, fear specifically. Similarly, Jenke and Peer (2018) examined the link between emotional intensity and physiological signals, but it was difficult to define the specific physiological responses to fear since they used an appraisal model that conceptualizes emotion based on the dimensions of relevance, implication, coping potential, and normative significances.

However, there are some studies examining the relationship between fear intensity and physiological responses from the perspective of discrete emotions (Aue et al., 2012; Choi et al., 2015; Vidmar et al., 2016; Yoshihara et al., 2016). Aue et al. (2012) used multiple pictures displaying spiders and snakes as fear-inducing stimuli and asked participants to rate their subjective fear for individual images, which demonstrated a significant effect of fear intensity (high vs. low) on physiological measures. However, this study did not investigate differences in response to the same fear-inducing stimulus, for example, a single picture of a spider, since multiple images of different types of animals were presented. To understand physiological changes in response to emotional stimuli, it is important to consider individual variability in experienced fear intensity and physiological responses. In addition, emotional responses to static stimuli, such as pictures, are less active than the responses to film clips, which present dynamic visual and auditory stimuli to participants (Gross & Levenson, 1995).

Yoshihara et al. (2016) used a film clip to induce the fear response and showed a significant negative correlation between the subjective ratings of fear and rate of change in fingertip temperature (FT). However, this study was based on a single sympathetic autonomic measure. Since the physiological responses to emotion elicitation comprise an integrated pattern, it is important to include a sufficient number of physiological measures to identify any variations (Schneiderman & McCabe, 1989). Choi et al. (2015) used a fear-inducing film clip and measured facial temperature, blinking rate, and brain activity (via electroencephalography, EEG), which reflects the reactions of the central nervous system (CNS). They proposed that facial temperature is more reliable than other physiological response for the evaluation of fear. Vidmar et al. (2016) measured the intensity of experienced emotion in response to two fear-inducing video clips and related it to changes in HR, BP, and SC; however, they did not find a statistically significant relationship. This might have been due to familiarity with the popularly known stimuli or a self-report bias from participants who did not want to admit to experiencing intense fear in an attempt to appear strong or stoic. These issues might have affected the results substantially since their study was based on only 20 participants.

In particular, the relationship between individual variability in experienced fear intensity and encompassing multimodal ANS responses has not been studied in detail from the perspective of discrete emotions. To address this issue, in the present study, we selected a short excerpt from a horror movie as the stimulus to avoid using static images or familiar video clips and to reliably elicit strong fear responses. In addition, the same stimulus was used for all participants to evaluate differences at the individual level. Instead of relying on one or two autonomic responses,

multiple physiological signals were measured to interpret ANS responses more effectively. Since the abovementioned previous studies were based on only 16–34 participants, we used a relatively large sample size for this study. We recruited 230 participants and asked them to identify their emotion and rate its intensity in response to the fear-inducing stimulus, which accounted for the independent variable of how the fear-inducing stimulus was individually experienced.

Our study had two objectives: First, we compared the multimodal physiological responses, including skin conductance level (SCL), skin conductance response (SCR), HR, FT, RR, and pulse transit time (PTT), induced by the fear-inducing and neutral film clips. These physiological variables were selected to represent emotion-related autonomic activation. We hypothesized that indices of peripheral physiological arousal will be higher while participants watch the fear-inducing film rather than the neutral film—as demonstrated by previous studies. We also examined the relationship between the participants' experienced intensity of fear in reaction to the fear-inducing stimulus and their physiological responses, and investigated whether the responses could predict fear intensity. As fear induces widespread sympathetic activation and is an emotion with high arousal and negative valence, we hypothesized that the participants' experienced fear intensity will statistically significantly correlate with their physiological responses related to sympathetic activation, and will be predicted by a linear combination of the physiological responses.

METHODS

Participants

We conducted an a priori power analysis to compute the necessary sample size using G*Power, a power analysis program for statistical tests (Faul et al., 2009). The result indicated that 164 participants would be required to obtain adequate power (0.95) for detecting a medium effect size of 0.25 at the standard .05 α error. Since the minimum sample size was relatively large, we recruited as many participants as possible before the end of the academic semester during which the study took place, in order to account for drop-outs (Simmons et al., 2011). A total of 230 undergraduate students (110 males; $M_{age} \pm SD$, 22.28 ± 2.05) took part in the study. None of the participants reported any history of medical illness or psychotropic medication use. The experimental procedure was explained to the participants, who provided written consent to participate in the study before the experiment began. In addition, $20 compensation was paid to each participant. This study was approved by the Institutional Review Board of Chungnam National University, Daejeon, South Korea (No. 201309-SB-004-01).

Emotion-Provoking Stimuli

Audiovisual film clips were used to elicit the participants' emotions, as they are more effective in presenting information related to developing integrated and sustained emotional responses than still pictures. The film clip used as the fear-inducing stimulus in the present study was 60 s and excerpted from a horror movie entitled *A Tale of Two Sisters* (Kim et al., 2003). We selected and excerpted the clip to elicit a strong fear response and to provide additional recovery time from the previous physiological baseline measurement session. Therefore, the fear-inducing stimulus was designed to intensify the emotion toward the end of its duration. The clip showed a ghost suddenly appearing and approaching a girl lying on her bed, which happened during the second half of the clip. The first half did not contain a scene that showed the ghost explicitly. Therefore, although the entire length of the clip was 60 s, only the second half was expected to elicit strong emotion-related physiological responses.

We conducted a preliminary experiment to evaluate the validity of the fear-inducing stimulus. A total of 50 college students (25 males, M_{age} 22.58 ± 1.24), who did not participate in the study proper, were presented with the fear-inducing film clip via a 38 in. screen in a classroom and asked to report the emotion they experienced during exposure to the stimulus. The participants had to choose one emotion out of 11 (i.e., happiness, sadness, anger, contempt, disgust, fear, surprise, boredom, interest, neutral, and other). Then, they were required to rate the intensity of the emotion they experienced on a 7-point Likert scale ranging from 1 (*least intense*) to 7 (*most intense*). In this experiment, all 50 participants chose the emotion of fear with an average intensity of 5.5 ± 0.83. A 60 s neutral film clip was chosen to evoke no emotion; it was excerpted from the same movie to match the contents, color, and hue with the fear-inducing film clip. The neutral film clip depicted a girl walking around a lake, house, and room. The average intensity of neutral stimulus was 5.1 ± 1.36.

Procedure

Prior to the experiment, the procedure was explained to the participants while they were sitting on a chair in the laboratory. To measure physiological signals, the electrodes for the sensors were attached to the participants. Physiological responses were measured during three sessions: at baseline and in the neutral and fear-inducing film sessions (see Figure 1). The duration of each session was 60 s. During the baseline session, the participants were instructed to rest. Then, the neutral and fear-inducing film clips were presented in a random order to the participants. After both clips were presented, the participants rested for 30 s and evaluated the emotions they experienced in response to the stimuli. First, the participants labeled the emotion they experienced (based on the above 11 categories). Next, they rated emotion intensity on the 7-point Likert scale. Finally, the participants identified and described the scene in which they experienced the strongest emotion during the fear-inducing film session.

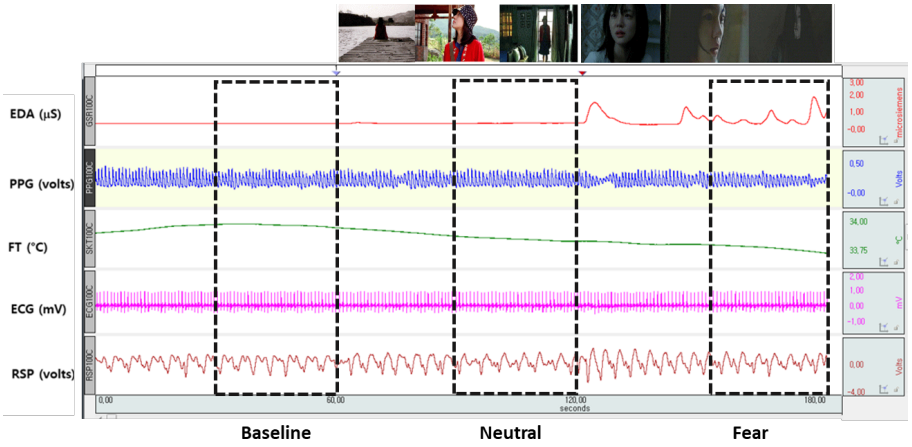

FIGURE 1.

Example of the recorded physiological data and analysis sections. The last 30 s interval of each session (dotted box) was selected for data analysis.

Physiological Data Acquisition and Feature Extraction

The MP100WS device and AcqKnowledge software (version 3.9.1) from BIOPAC Systems Inc. (Goleta, CA, USA) were used to measure and analyze the participants' physiological signals. Electrocardiograms (ECGs) were recorded using a lead I configuration, in which the electrodes were attached to the right wrist, left wrist, and left ankle. The ECG signal was low-pass filtered (0–125 Hz) and sampled at 250 Hz. The EDA signals were recorded by applying a constant voltage of 0.5 V between the volar surfaces of the proximal phalanx of the forefinger and middle finger of the nondominant hand. The EDA signal was low-pass filtered (0–10 Hz) and sampled at 100 Hz. The FT was measured at the volar surface of the distal phalanx of the little finger of the nondominant hand. The FT signal was low-pass filtered (0–0.15 Hz) and sampled at 1 Hz. The photoplethysmograph (PPG) signal was measured from the volar surface of the distal phalanx of the thumb of the nondominant hand. The PPG sensor was strapped around the thumb, which prevented interference by external light or a decrease in finger skin temperature that causes vasoconstriction. The PPG signal was low-pass filtered (0–10 Hz) and sampled at 250 Hz. The respiration (RSP) was measured using a respiration belt transducer, which was band-pass filtered (0.05–1 Hz) and sampled at 50 Hz.

In total, six features were extracted from the physiological signals. As an ECG feature, mean HR was used to represent heart activity, which was calculated from R peak-to-R peak intervals. As EDA features, SCL and SCR were used to reflect sweat secretion. SCL was extracted from the raw EDA signal using a 0.15 Hz low-pass filter and sampled at 1 Hz. The mean SCL amplitude was evaluated over the 30-s period for each session. The SCRs were considered valid if they showed an onset in the 1–4 s poststimulus period and showed a peak during the 5 s subsequent to the onset (Boucsein et al., 2012). Then, all valid SCRs greater than the threshold of 0.078 μS (minimal slope of 0.007 μS/s, maximal half recovery time of 10 s) were averaged across the 30 s period for each session (Stemmler, 1992; Stemmler et al., 2001). The SCR amplitude was calculated as the change from the onset of the response to the peak of the response (Alexander et al., 2005). The mean FT was calculated by averaging FT values over 30 s. As a PPG feature, PTT was used, which was defined as the time between the ECG R peak and the systolic peak in the PPG pulse signal. RR was defined as the number of breaths per minute, which was counted from RSP signals.

Data Analysis

The self-ratings indicated that all participants in the current study experienced the most intense fear during the last 30 s of the fear-inducing clip. For each session, the last 30 s interval was selected from the total length, and physiological features during this interval were evaluated. Figure 1 illustrates examples of the physiological signals collected and the 30 s intervals selected for data analysis.

All data were analyzed using the Statistical Package for Social Sciences (SPSS), version 21.0 (SPSS Inc, Chicago IL). To analyze the differences between the physiological responses during the neutral and fear-inducing sessions, paired-sample t-tests were performed on the values after subtracting the baseline. Nonparametric Spearman's rank correlation coefficients were calculated to investigate the relationships between psychological and physiological responses (i.e., fear minus baseline) as the psychological responses were not distributed normally. The strength of the correlation coefficients was evaluated using the following criteria (Ratner, 2009): the values of 1 and -1 indicate a perfect linear relationship, values between .7 and 1 (also, -.7 and -1) indicate a strong relationship, values between .3 and .7 (-.3 and -.7) indicate a moderate relationship, and values between 0 and .3 (0 and -.3) indicate a weak relationship. A level of significance of .05 was chosen for all tests, and 95% CI were calculated for each physiological response. To correct for comparing multi-

TABLE 1.
Differences between physiological responses during the neutral and fear-inducing sessions ($N = 230$, $df = 228$)

Parameters	Neutral	Baseline	Fear	Baseline	Mean difference (std. error difference)	95% CI	*t*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*					
SCL (μS)	.01	.07	.19	.20	.18(.02)	.14–.21	10.58	< .001	.81
SCR (μS)	.10	.45	2.06	1.24	1.95(.10)	1.75–2.15	19.24	< .001	1.56
HR (bpm)	.40	3.38	7.27	11.24	6.86(.91)	5.08–8.65	7.58	< .001	.60
FT (° C)	.07	.24	−.07	.22	−.14(.02)	−.18–−.09	-5.63	< .001	.38
PTT (ms)	-.65	6.64	−13.63	17.66	−12.98(1.45)	−15.83–−10.13	−8.96	< .001	.63
RR (breaths/min)	-.37	1.31	.72	1.44	.40(.09)	.22–.59	4.30	< .01	.51

Note. SCL = skin conductance level; SCR = skin conductance response; HR = heart rate; FT = fingertip temperature; PTT = pulse transit time; RR = respiratory rate.

ple physiological features, we used the Bonferroni correction method and adjusted α levels by dividing .05 by six, the number of features in the present study. Multiple linear regression with stepwise forward entry was conducted to determine whether a linear combination of the physiological responses could predict the experienced fear intensity.

RESULTS

Psychological Responses to the Fear-Inducing Stimulus

The appropriateness of the two film clips was evaluated by calculating the percentage of the participants who experienced the intended emotion. The fear-inducing film clip showed 92.5% appropriateness. The effectiveness of the film clips was defined as the average intensity ± *SD* measured using the 7-point Likert scale. The fear film clip showed effectiveness on a level of 5.95 ± 1.36. Figure 2 shows the distribution of the participants' self-ratings of the intensity of the experienced fear, which was mostly between 5 and 7. These results suggest that the experienced emotions indicated by the participants' ratings were consistent with the intended emotion for the fear-inducing stimulus. Similarly, the neutral film clip showed 94.8% appropriateness and 5.23 ± 1.22 effectiveness.

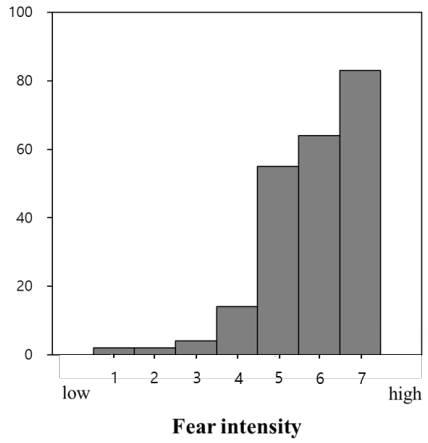

FIGURE 2.
Distribution of the self-reported intensity ratings (x-axis: intensity, y-axis: frequency).

Physiological Responses to the Fear-Inducing Stimulus

The paired *t*-tests indicated that physiological responses changed significantly after the presentation of the emotional stimulus in the fear-inducing session, relative to the neutral session (see Table 1). All six physiological features showed significantly different responses between the neutral and fear-inducing sessions. Skin conductance level ($t = 10.58$, $p < .001$), SCR ($t = 19.24$, $p < .001$), HR ($t = 7.58$, $p < .001$), and RR ($t = 4.30$, $p = .001$) increased in the fear-inducing film session to a greater degree than in the neutral film session. In contrast, FT ($t = -5.63$, $p < .001$) and PTT ($t = -8.96$, $p < .001$) decreased in the fear-inducing film session to a greater degree than in the neutral film session. The physiological feature values before subtracting the baseline are shown in Figure 3, which indicates that the physiological responses to the fear-inducing clip were greater than those to the neutral film clip, and that the physiological features measured from the neutral session were similar to those from the baseline.

TABLE 2.
Correlation Between The Intensity of Experienced Fear and Physiological Responses (Fear Minus Baseline) to the Fear Stimulus (Bonferroni Correction for Multiple Comparisons, $N = 230$, $df = 228$)

	Intensity	SCL	SCR	HR	FT	PTT	RR
Intensity	1.00	−.14*	.18*	.27*	−.33	−.43*	−.26*
SCL	−.14*	1.00	.39*	−.10	.08	.11	.11
SCR	.18*	.39*	1.00	−.01	−.11	−.00	−.12
HR	.27*	−.10	−.01	1.00	−.05	−.26*	−.12
FT	−.14*	.08	−.11	−.05	1.00	−.08	−.026
PTT	−.43*	.11	−.00	−.26*	−.08	1.00	.13
RR	−.25*	.11	−.12	−.12	−.02	.13	1.00

Note. SCL = skin conductance level; SCR = skin conductance response; HR = heart rate; FT = fingertip temperature; PTT = pulse transit time; RR = respiratory rate.

* $p < .0083$

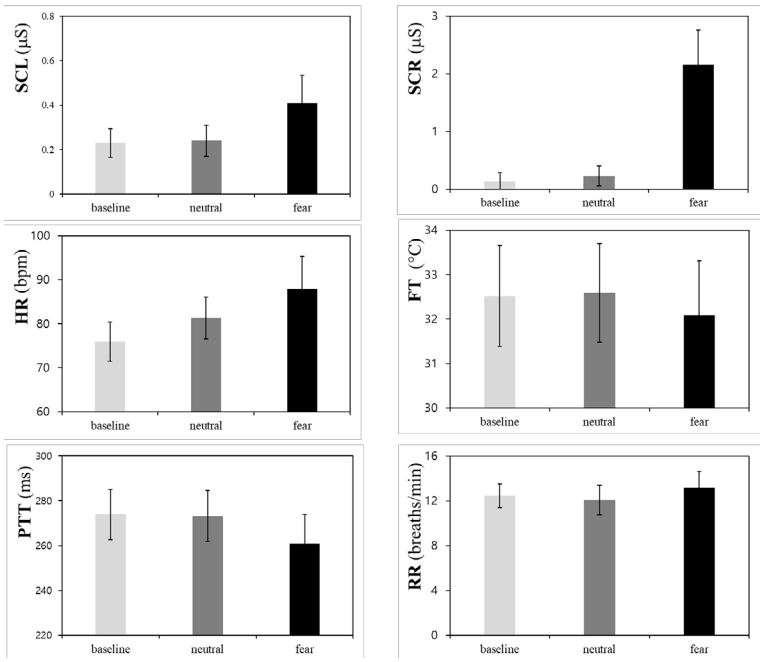

FIGURE 3.

Physiological responses measured during the baseline, neutral, and fear-inducing sessions.

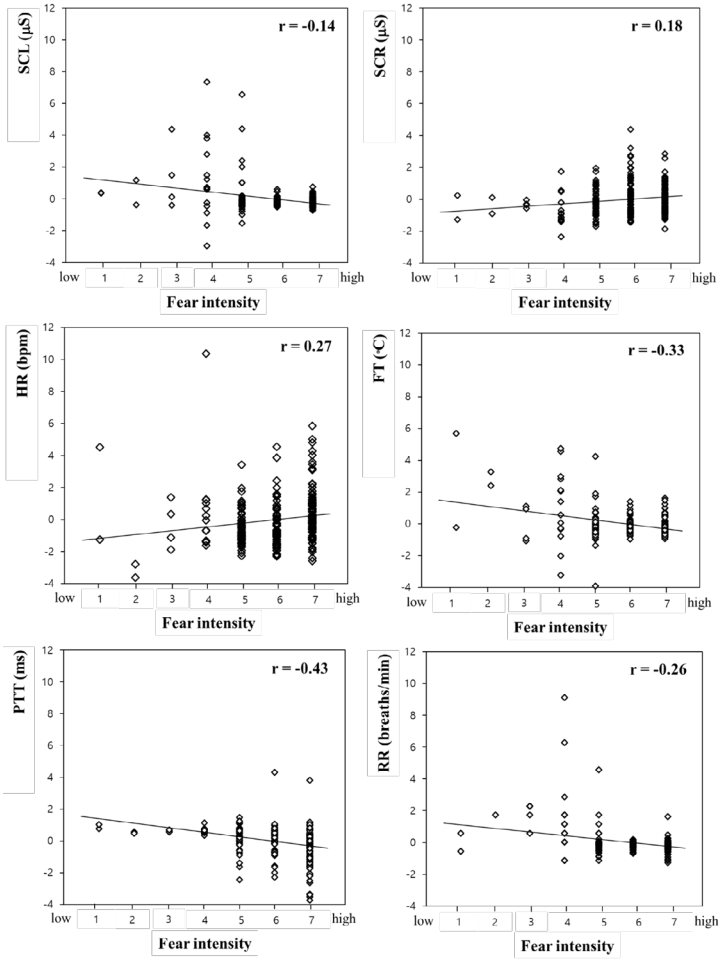

FIGURE 4.

Correlation between fear intensity and changes in physiological responses (fear minus baseline).

TABLE 3.
Multiple Linear Regression Analysis Predicting Experienced Fear Intensity Based on Physiological Responses, $N = 230$, $df = 223$

Predicted variable	Predictors	Unstandardized coefficients		Standardized coefficients	t	p	95% CI of B	Collinearity statistics	
		B	SE	β				Tolerance	VIF
Intensity of experienced fear	SCL	−.264	.073	−.211	−3.61***	< .001	−.39−−.14	.770	1.299
	SCR	.165	.048	.184	3.47**	< .001	.09−.24	.940	1.064
	HR	.053	.006	.467	8.97***	< .001	.04−.06	.969	1.032
	FT	−.515	.097	-.278	−5.29***	< .001	−.68−−.35	.954	1.049
	RR	−.074	.023	-.191	-3.24**	< .01	−.11−−.04	.754	1.325
$R = .694$, $R^2 = .482$, Adjusted $R^2 = .469$, $F(5, 224) = 12.039$, $p < .001$, Durbin-Watson's $d = 1.606$									

Note. SCL = skin conductance level; SCR = skin conductance response; HR = heart rate; FT = fingertip temperature; PTT = pulse transit time; RR = respiratory rate.
* $p < .05$, ** $p < .01$, *** $p < .001$

Relations Between the Intensity of Experienced Fear and Physiological Responses

Table 2 and Figure 4 show the relationships between the participants' intensity of experienced fear and physiological responses (i.e., fear minus baseline) to the fear-inducing stimulus. Fear intensity was positively correlated with SCR ($rs = .18$, $p = .005$) and HR ($rs = .27$, $p < .001$), and negatively correlated with SCL ($rs = −.14$, $p = .008$), FT ($rs = −.33$, $p < .001$), PTT ($rs = −.43$, $p < .001$), and RR ($rs = −.26$, $p < .001$). The strength of the correlation between fear intensity and PTT was moderate ($r = −.43$) and for the correlations between the intensity and SCL ($r = −.14$), SCR ($r = −.18$), HR ($r = −.27$), FT ($r = −.23$), and RR ($r = −.26$), it was weak. In addition, there were significant correlations between physiological responses, that is, a positive correlation between SCL and SCR ($rs = .39$, $p < .001$) and a negative correlation between HR and PTT ($rs = −.26$, $p < .001$; see Table 2).

We performed multiple linear regression analysis with stepwise forward entry to examine whether a combination of physiological responses can predict the fear intensity (see Table 3). A significant regression equation was found ($p < .001$), with R = .694. Except for PTT, SCL ($p < .001$), SCR ($p = .001$), HR ($p < .001$), FT ($p < .001$), and RR ($p = .001$) were significant predictors, which explained 48.2% of the variance in fear intensity. Fear intensity was influenced by the physiological responses in the following order: HR (β = .467), FT (β = -.278), SCL (β = −.211), RR (β = −.191), and SCR (β = .184). Skin conductance response and HR were positively related to the intensity, whereas SCL, FT, and RR were negatively related. The Durbin-Watson test showed that there was no first order auto-correlation ($d = 1.606$). Tolerance (.7–.97) and variance inflation factors (VIF, 1.03–1.33) indicated that there was no multicollinearity. The analysis yielded the following linear model:

$$\text{Intensity}_{\text{fear}} = 5.212 - .264(\text{SCL}) + .165(\text{SCR}) + .053(\text{HR}) - .515(\text{FT}) - .074(\text{RR}).$$

DISCUSSION

Psychological Responses to the Fear-Inducing Stimulus

In the present study, we used a film clip as an emotional stimulus to induce intense fear. The fear-inducing film clip showed an appropriateness of 92.5% and scored 5.95 (out of 7) for effectiveness, suggesting that it was effective in provoking fear. These results are consistent with previous studies, which have suggested that film clips are more effective than still pictures in delivering information for inducing emotional responses.

Physiological Responses to the Fear-Inducing Stimulus

Our results demonstrated that SCL, SCR, HR, and RR increased in response to the fear-inducing stimulus, which is consistent with previous findings. Unlike other physiological features, SCL and SCR are only affected by the sympathetic response, specifically cholinergic sympathetic changes, and are not affected by parasympathetic responses. Therefore, increases in SCL and SCR during the fear-inducing session reflected an increased activation of the sweat glands and sympathetic arousal.

Cardiac activity is affected both by the sympathetic and parasympathetic nervous systems. An increased HR can be caused by either sympathetic activation or parasympathetic inhibition. Therefore, it is not certain which mechanism underlies the increased HR unless other physiological signals are accounted for. In this study, both HR and RR increased during the fear-inducing session, which may indicate activation of the sympathetic nervous system. Similarly, in previous studies, increased HR was observed with a shorter period of respiration during the fear state . However, conflicting results on fear-induced HR changes have also been reported, for which a decreased HR was observed during the fear-inducing session. Furthermore, changes in HR induced by fear-inducing stimuli may be dependent on the appraisal processes or stimuli types (e.g., slide, cognitive task,

and imagery). For example, if a person perceives a stimulus as threatening and imminent, their cardiac activity increases as a reaction to fear. In contrast, HR decreases if certain types of stimuli, such as attentional task demands, are used for fear-inducing stimuli. Thus, it is important to account for appraisal processes and stimuli types when interpreting HR changes. In the present study, the participants' self-reports of the emotion induced by the fear-inducing film suggest that they experienced the stimulus as threatening and fearful, as if they were in the protagonist's place. When considering the process of appraisal of the fear-inducing stimulus based on these results, the increased HR found in the present study may indicate activation of the sympathetic nervous system's fight-or-flight reaction. The RR defines how often the respiration cycle repeats itself each minute. Fear is usually associated with increased arousal and induces a respiratory pattern characterized by faster and deeper breathing. Similarly, in the present study, the fear-inducing stimulus provoked an increased RR. As previous studies demonstrated, we observed decreases in FT and PTT during the fear-inducing session. Pulse transit time is an indicator of arterial BP, and a decrease in PTT is significantly correlated with increased BP. A simultaneous decrease in FT and PTT has been reported widely in previous research on fear, which suggests α-adrenergic vascular changes or increased vasoconstriction.

Relations Between the Fear Intensity and Physiological Responses

The psychological responses during the fear-inducing session were positively correlated with SCR and HR, while they were negatively correlated with SCL, FT, PTT, and RR. In addition, we demonstrated that the intensity of experienced fear can be predicted using a multiple linear regression of features derived from physiological measures (SCL, SCR, HR, FT, and RR). Fear is an emotion with high arousal and negative valence. Previous studies have shown that SCR increases when arousal increases, and HR increases when an emotion becomes more unpleasant (more negative valence). These findings are consistent with our results showing positive correlations between experienced fear intensity and SCR and HR. However, the negative correlation between experienced fear intensity and SCL and RR was not consistent with previous findings. Bradley and Lang (2000) and Lang et al. (1993)demonstrated that SCL and RR increased linearly with the arousal intensity of emotional stimuli. However, a negative relationship between fear intensity and SCL has been reported from previous studies using a real-life induction context (radio play, announcement of uncontrollable event, and sudden light outage) and music excerpts (Stemmler, 1989; Krumhansl, 1997) as fear-inducing stimuli. Kreibig (2010) suggested that fear paradigm elicits a stronger degree of self-involvement, which leads to higher perceptions of threat imminence (Bradley & Lang, 2000; Craske, 1999; Fanselow, 1994; Lang et al., 1997). In general, fear is associated with sympathetic activation, but threat imminence is characterized by immobilization and sympathetic inhibition (Kreibig, 2010).

Since the film clip used in this study included the scene where a ghost suddenly appears, we cannot rule out the possibility that the participants who reported intense fear also experienced the emotion of surprise. Kragel and LaBar (2013) showed decreased RR in response to surprise induced by music and film clips. Feleky (1916) used autobiographical recall to elicit wonder (surprise) and found decreased RR. She suggested that a "decided inspiratory pause" was a distinct feature of the characteristic breathing curve of wonder and was observed similarly, but to a lesser degree, in the fear breathing curve. Nonetheless, other previous studies investigating surprise have shown increased RR (Kreibig, 2010; Siedlecka & Denson, 2019), and no clear conclusion can be derived on respiratory response to the emotion of surprise. Therefore, a more in-depth study is required to understand and explain decreased RR with increasing fear intensity. Moreover, our results indicate that FT decreased with increased experienced fear intensity, which was previously reported by Yoshihara et al. (2016). As mentioned, PTT decreased compared to the baseline while watching the fear-inducing stimulus clip and was negatively correlated with experienced fear intensity. Based on these results, we can conclude that as fear intensity increases, there are increased α-adrenergic vascular changes and increased vasoconstriction.

Limitations

Our results demonstrated a significant relationship between fear intensity and physiological responses to the fear-inducing stimulus. However, the present study had some limitations. First, since fear intensity ratings were not distributed normally, we used Spearman's rank correlation as a nonparametric statistical method. As shown in Figure 2, the fear intensity ratings mostly scored above 5 on a 7-point Likert scale. Second, although we have demonstrated the validity of the fear-inducing stimulus in the preliminary study (see Methods section) and the study proper, we did not consider the other emotions experienced by the participants and to what extent the clip had achieved specificity for the target emotion. This is because all 50 participants in the preliminary study reported fear as the emotion they experienced during exposure to the fear-inducing stimulus, and based on these results, we decided to evaluate only the fear response. Third, we evaluated fear intensity, but did not account for the effect of the participants' motivational states. Previous studies have suggested that changes in physiological responses depend not only on the emotional stimuli (e.g., threatening, violent death, etc.) but also on cognitive factors such as the participants' fear reactions based on motivational states, that is, defensive and appetitive (Bradley et al., 2001; Lang et al., 1997). In addition, some participants may experience phobic fear depending on the context of the stimuli. Since we used a single fear-inducing stimulus, we did not investigate

how the participants would respond to different contexts of the stimuli, which limits comparisons to other studies on physiological responses to fear-inducing stimuli. Fourth, we were unable to investigate the interaction between the sympathetic and parasympathetic activations in the physiological responses. In particular, our results did not differentiate between the influences or latencies of the sympathetic and parasympathetic nervous systems in response to the fear-inducing stimulus. Therefore, additional analyses of physiological responses such as heart rate variability (HRV) are needed to differentiate the roles of the sympathetic and parasympathetic nervous systems in regulating fear responses. For example, HRV spectral analysis combined with respiration frequency data can be used to evaluate sympathetic and parasympathetic activities by calculating low- and high-frequency areas in the HRV power spectrum, respectively. This analysis has been used to investigate correlations between emotional intensity in response to stimuli and HRV spectral components. However, we did not conduct HRV analysis in the present study, because the length of the data (30 s) was too brief to obtain reliable results, for which at least 5 min duration is generally recommended. Lastly, despite the positive correlation between SCR and SCL, we found an opposite relationship with fear intensity ratings for these two skin conductance features. SCR, which represents phasic response, increased as fear intensity increased. Changes in phasic activity are characterized by a steep incline and a slow recovery, and this pattern would similarly occur in SCRs during the fear-inducing session. Further analyses of specific features, such as the number of SCRs (nSCR) and temporal characteristics of the SCR waveform, including onset latency, rise time, and half-recovery time, are needed to understand the increase in SCR. Although these temporal characteristics are not as commonly quantified as amplitude (Dawson et al., 2007), half-recovery time, for example, is defined as the time it takes for an SCR to decrease to half its peak value and reflects the rate at which an emotional response, particularly fear or anxiety, dissipates (Newrith et al., 2006). Therefore, slower recovery rates are related to slower dissipation of autonomic activation (Newrith et al., 2006). An increase in SCR can be induced by high nSCR with short recovery time but also by low nSCR with long recovery time. In addition, instead of taking the average, the 30-s interval can be subdivided into a sequence of short moving windows (e.g., 5-s or 10-s) using the participants' self-reports. Then, temporal changes in fear intensity during stimulus presentation can be tracked and related with SCRs, which would provide more information on how experienced fear is associated with the ANS response.

Implications

Although previous studies have examined the differences in physiological changes in response to basic emotions using mainly HR, SCR, and BP during fear-inducing sessions, they did not find significant relationships between fear intensity and physiological responses (Vidmar et al., 2016). Yoshihara et al. (2016) only indicated a negative correlation between subjective fear ratings and the rate of change in FT. In addition, to the best of our knowledge, there has been no study on the correlations between experienced fear intensity and PTT or RR. We also discovered individual differences in psychological responses during the presentation of the fear stimuli by studying a large sample of 230 individuals. The present findings suggest that physiological changes during the experience of fear are associated with the cholinergic sympathetic and α-adrenergic vascular activations and myocardial β-sympathetic excitation. Finally, we suggest that the psychological responses of fear can be derived from a multiple linear regression model of peripheral physiological measures, which supports the use of multimodal physiological signals for recognizing and quantifying human emotions.

ACKNOWLEDGEMENTS

This work was supported by the Institute for Information & Communications Technology Promotion (IITP) grant funded by the Korea government (MSIT) (No. 2015-0-00062). This work was also supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1F1A1049236).

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RECEIVED 26.02.2020 | ACCEPTED 18.08.2020