IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 29 May 2024, accepted 28 July 2024, date of publication 2 August 2024, date of current version 28 August 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3437671

RESEARCH ARTICLE

Analysis of Acute Stress Reactivity and Recovery in Autonomic Nervous System Considering Individual Characteristics of Stress Using HRV and EDA

JINHAK LEE[1], HO BIN HWANG[1], SEUNGJAE LEE[1], JAYON KIM[2], JEYEON LEE[1], SANGHAG KIM[3], JUNG HEE HA[4], YOOJIN JANG[4], SEJIN HWANG[2], HOON-KI PARK[5], JONGSHILL LEE[1], AND IN YOUNG KIM[1]

[1]Department of Biomedical Engineering, Hanyang University, Seoul 04763, South Korea
[2]Department of Anatomy and Cell Biology, College of Medicine, Hanyang University, Seoul 04763, South Korea
[3]Department of Sociology, Hanyang University, Seoul 04763, South Korea
[4]Graduate School of Counseling Psychology, Hanyang University, Seoul 04763, South Korea
[5]Department of Family Medicine, Hanyang University, Seoul 04763, South Korea

Corresponding authors: Jongshill Lee (netlee@hanyang.ac.kr) and In Young Kim (iykim@hanyang.ac.kr)

This work was supported by 'Smart HealthCare Program(www.kipot.or.kr)' funded by the Korean National Police Agency (KNPA, Korea). [Project Name: Development of wearable system for acquiring lifelog data and customized healthcare service for police officers/Project Number: 220222M04]; and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A5A7025522).

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board (IRB) of Hanyang University under Application No. HYUIRB-202009-032-3.

ABSTRACT Stress is a complex factor that simultaneously triggers psychological and physiological changes in humans. However, research on the relationship between stress's psychological and physiological aspects has been limited. This study examined the psychological and physiological aspects of stress in 56 police officers using the Perceived Stress Scale (PSS) and the Connor-Davidson Resilience Scale (CD-RISC). Participants performed the Trier Social Stress Task (TSST), and their physiological responses were monitored via wearable sensors measuring heart rate variability (HRV), electrocardiogram (ECG), and electrodermal activity (EDA). We grouped the participants into three groups based on the PSS and CD-RISC scores. We analyzed the differences in stress reactivity during stress situations and stress recovery following stress situations among the groups. Results showed that higher perceived stress (PSS) was linked to reduced stress reactivity, indicated by lower EDA parameters (SCR std and SCR amplitude) during stress. Conversely, higher resilience (CD-RISC) correlated with better stress recovery, indicated by improved HRV parameters (HR, pNN30, and pNN50) post-stress. These findings highlight how psychological factors influence physiological stress responses and may aid in developing personalized stress assessments.

INDEX TERMS Psychophysiological stress assessment, stress reactivity, stress recovery, heart rate variability (HRV), electrodermal activity (EDA), autonomic nervous system (ANS).

I. INTRODUCTION

Stress response is defined as an evoked response when our body perceives any stimuli that exceeds an organism's adaptive capacity and disrupt homeostasis [1]. The stress response includes physiological as well as psychological reactions, which are mediated by a complex interplay of the hypothalamic-pituitary-adrenal (HPA) axis, the autonomic nervous system (ANS), metabolic system, and the immune systems. These systems are dynamic biological processes

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

designed to cope with both internal and external stress, facilitating adaptation to environmental challenges, which is referred as "allostasis" [2]. This, in turn, enhances an individual's possibility of survival in perilous situations and aids in the adaptation to stressful circumstances [3]. However, prolonged or repeated exposure to stressor (i.e., allostatic load) can lead to a cascade of negative health outcomes, including cardiovascular diseases [4], diabetes [5], cancer susceptibility, as well as mental disorders such as sleep disorder, and anxiety disorders [6], [7], [8], [9], [10].

It is well known that there are considerable individual differences in the perception and adaptation to potentially stressful situations, and the body's responses to stressors can vary among individuals, even when experiencing the same stressor [11], [12]. Besides the genetic and epigenetic alterations, the degrees of the allostatic load and imbalance of the homeostasis, influenced by an individual's experiences of stress encountered during their daily life and shaped by experiences accumulated over an extended period, has been accounted for such heterogeneous response. The variability encompasses two aspects: 1) stress reactivity, reflecting differences in the magnitude, duration, and frequency of response; and 2) the inhibition of stress response, representing an ability to cease the responses after stress [13]. As allostatic overload has been reported to be associated with a heightened susceptibility to various diseases and chronic disorders [13], understanding and characterizing the diversity of stress response can be important in elucidating the etiology and developing personalized interventions for stress management.

However, studies in the past that investigated the stress response often lacked con-sideration for the individual variability and mostly analyzed the psychological and physiological responses to stress separately. A few recent studies have attempted to comprehensively explore the intricate relationship between the inter-individual contextual factors and immediate physiological stress responses [14], [15]. For instance, Ginty and Conklin [14] studied the association between perceived stress in life and stress-induced cardiovascular changes in healthy individuals. The authors grouped the participants based on questionnaire scores that assess the perceived stress level and compared the heart rate (HR) between the groups. The results showed that individuals with heightened psycho-logical perceived stress exhibited reduced HR changes compared with other groups. Hourani et al. [15] reported a significant negative correlation between stress responses with the low-frequency parameter of heart rate variability (HRV), linking psychological factors to physiological parameters. Additionally, several prior studies investigated the relationship between psychological factors and physiological stress responses in patients with anxiety disorders or post-traumatic stress disorder (PTSD) [16], [17], [18]. However, the inter-individual variability of physiological responses to stress, affected by the daily life stress level, still remains ambiguous due to differences in participant characteristics, stress induction protocols, and psychophysiological measures used for stress analysis. Moreover, most studies used only a limited set of ANS response indicators, thus failing to capture the full spectrum of physiological characteristics during the acute stress response.

In this study, we explored how individuals' stress reactivity and recovery vary according to the perceived stress level and resilience, assessed by the Perceived Stress Scale (PSS) and Conner-Davidson Resilience Scale (CD-RISC) test, accordingly. Stress reactivity refers to acute changes occurring when exposed to a stressor, while stress recovery is the process of returning the body or mind to balance after stress [19]. Here, we sub-grouped the healthy participants based on the questionnaires scores and compared the profound differences in the physiological responses to stress between the groups in terms of the stress reactivity and recovery after the acute stress induction using the Trier Social Stress Test (TSST) protocol. We measured wearable sensor-based physiological signal including HRV and electrodermal activity (EDA). We tried to analyze the degree of stress reactivity and recovery based on features extracted from the physiological data obtained during stress-inducing experiments for police officers who are routinely exposed to stressful situations.

II. METHODS

A. DATA ACQUISITION

1) DATA DESCRIPTION

We recruited participants on a first-come, first-served basis through recruitment notice. The dataset comprises 56 participants (51 males and five females) and includes physiological signals (HRV, EDA) as well as responses from questionnaires (PSS, CD-RISC). All participants were healthy police officers in their third year of service with no history of mental illness. Three participants who exhibited excessive motion artifacts in their EDA signals were excluded from the analysis [20]. This study was conducted following the guidelines of the Helsinki Declaration with the approval of the Institutional Review Board of Hanyang University Hospital. All participants provided informed consent before the experiments (HYUIRB-202009-032-3).

2) PSYCHOLOGICAL STRESS DATA ACQUISITION

Participants completed personal information surveys, which collected information on age, marital status, education, and the institution of appointment, and psychological stress questionnaires before the stress experiment. The questionnaires used the PSS and CD-RISC to measure the psychological factors of stress. The internal consistency of the questionnaire scores for all participants was evaluated using Cronbach's α [21].

The PSS consists of 10 items and reflects the perceived level of stress based on per-sonal stress experiences in the past month [22]. This questionnaire is commonly used as an indicator of chronic stress. The Cronbach's α for the PSS used in this psychological resilience level following stress situations [23]. In this study, the Cronbach's α for the

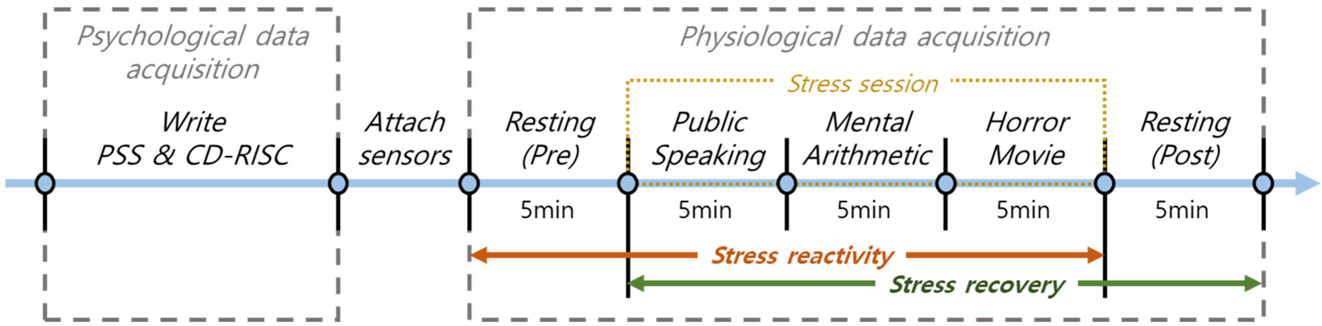


FIGURE 1. Experimental protocol.

CD-RISC was 0.871, demonstrating a high level of internal consistency [21]. A summary of the results of the participants' questionnaires is presented in Table 1.

TABLE 1. Participant characteristics.

Characteristic	Value
Participants	N = 53 (48 males, 5 females)
Age	M = 30.2 (SD = 3.8)
Marital status	
Married	N = 15 (28.3%)
Single	N = 38 (71.7%)
Education	
High school	N = 18 (34.0%)
College	N = 4 (7.5%)
University	N = 28 (52.8%)
Graduate school	N = 3 (5.7%)
Employment period	
< 3 years	N = 2 (3.8%)
3–5 years	N = 45 (84.9%)
> 5 years	N = 6 (11.3%)
Perceived Stress Scale	M = 15.72 (SD = 3.71)
Conner-Davidson Resilience Scale	M = 65.28 (SD = 10.11)

3) PHYSIOLOGICAL STRESS SENSORS

We measured HRV signals using the Polar H10 HR monitor (Polar Electro Oy, Kempele, Finland) with the Polar Pro Chest Strap [24]. The Polar H10 was connected to the 'Polar Sensor Logger' app, through which R-R intervals (RRIs), also known as HRV, were collected along with timestamps. EDA was measured using a homemade EDA monitoring system. The homemade EDA system consists of a microcontroller (STM32F407IEH6, STMicroelectronics, Switzerland), Bluetooth module (PAN1321i, Panasonic, Japan), and biopotential measurement component (ADS1299, TEXAS INSTRUMENTS, USA). The homemade EDA system was verified for reliability through contrast evaluation with BIOPAC MP150, which is commonly used in stress analysis, and details of this are included in the supplementary materials. EDA data were sampled at 250 Hz from the second phalanges of the index and middle fingers of the non-dominant hand of each participant, as shown in Figure 1.

4) STRESS PROTOCOL

All participants participating in the experiment visited the laboratory alone at the same time on different dates and conducted the experiment. They underwent stress protocols in a controlled laboratory environment as protocol depicted in Figure 2. The stress-inducing experiment comprised a total of five sessions, with two non-stress sessions (pre-resting and post-resting) and three stress sessions (public speaking, mental arithmetic, horror movie). After the participants completed the questionnaires and sensors were attached, they underwent the experimental protocol in the following order: pre-resting, public speaking, mental arithmetic, horror movie, and post-resting. For each session, the experimenter manually recorded the start time. During the non-stress sessions, participants sat in comfortable chairs and rested. To induce acute mental stress, the participants underwent a stress-inducing task consisting of the TSST (public speaking and mental arithmetic) and watching a horror movie. In the public speaking session, participants conducted job interviews related to police duties in front of two interviewers. In the mental arithmetic session, all participants started from 2023 and subtracted 17; the participants then repeated the calculation. If a participant provided an incorrect answer, the supervisors requested them to start over from the beginning. In the last session of the stress-inducing experiment, participants watched a clip from a horror movie. Each session lasted for 5 min, and HRV and EDA were continuously measured during the sessions.

FIGURE 2. EDA monitoring system.

B. DATA PROCESSING

1) QUESTIONNAIRE GROUPING

We performed a grouping based on PSS and CD-RISC questionnaire scores to analyze the stress reactivity and recovery of physiological signals by different levels of psychological stress as assessed by the stress questionnaires. The two stress

TABLE 2. HRV and EDA stress parameters.

Parameters	Definition
Heart rate variability	
HR	Mean heart rate per min
RMSSD	Square root of the mean of the successive differences between adjacent R-R intervals
pNNx (pNN30, pNN50)	Percentage of successive differences between R-R intervals greater than x ms
Low frequency (LF-log)	Low frequency band energy of HRV signal in frequency band (0.04–0.15 Hz)
High frequency (HF-log)	High frequency band energy of HRV signal in frequency band (0.15–0.4 Hz)
LF/HF ratio	Ratio of LF-log and HF-log
Electrodermal activity	
Peak count	Mean of the number of SCR peaks per minute
SCR median	Median of SCR component
SCR std	Standard deviation of SCR component
SCR peak amplitude mean	Mean of SCR peak amplitude
SCR peak amplitude std	Standard deviation of SCR peak amplitude
SCR peak amplitude max	Max of SCR peak amplitude
SCR peak risetime mean	Mean of SCR peak risetime
SCR peak risetime std	Standard deviation of SCR peak risetime
SCR peak risetime max	Max of SCR peak risetime
SCL median	Median of SCL component
SCL std	Standard deviation of SCL component

questionnaires measure the levels of perceived stress and stress resilience, respectively, and they do not have specific cutoff scores for diagnosing specific diseases [25]. Therefore, participants were grouped based on tertiles for each questionnaire score [26]. The participants were classified into one of the following groups according to their PSS scores: low perceived stress, moderate perceived stress, or high perceived stress. The participants were also divided into groups of low resilience, moderate resilience, or high resilience based on their CD-RISC scores.

2) SIGNAL SYNCHRONIZE

We utilized the timestamps provided by each system to achieve synchronization at one-second intervals. Additionally, we aligned the signal timestamp to the start times of each stress session.

3) HRV PREPROCESSING AND EXTRACTION OF STRESS PARAMETERS

Preprocessing was carried out on the HRV data to remove noise caused by motion artifacts. Data points in the HRV data that deviated more than 3 standard deviations (SD) from the mean were defined as outliers due to noise and were removed [27]. Since HRV signals are nonlinear, cubic spline interpolation was used to connect the removed data segments [28]. We extracted time domain and frequency domain parameters of HRV that have been previously used to distinguish between rest and stress states in stress classification studies. Time domain parameters included the mean of heart rate (HR), square root of the mean squared difference between successive RR intervals (RMSSD), and the proportion of successive differences between RR intervals greater than x milliseconds (pNN30, pNN50) and frequency domain parameters including high frequency (HF, 0.15–0.4 Hz), low frequency (LF, 0.04–0.15 Hz), and the HF/LF ratio were extracted [29]. The HF and LF parameters in the frequency domain were calculated as the energy in each frequency band, and a log transform was applied for analysis. The extracted HRV parameters are summarized in Table 2. All signal processing and parameter extraction processes were performed using in-house scripts (MATLAB R2021b).

4) EDA PREPROCESSING AND EXTRACTION OF STRESS PARAMETERS

We detected and removed motion artifacts in the EDA signal, focusing on segments with a rapid increase. We then applied a 4th order low-pass Butterworth filter (cut-off frequency = 0.3 Hz) to the EDA signal to eliminate high-frequency noise. To help readers understand, we included examples in the supplementary materials in the changing waveform during the EDA preprocessing process. To analyze the trends in EDA signal changes due to stress induction, we applied Z-score normalization. The preprocessed EDA signal was decomposed into skin conductance response (SCR) and skin conductance level (SCL) components using the convex optimization-based cvxEDA algorithm [30]. For stress reactivity and recovery analysis, we extracted parameters from the SCR component, including median, std, peak count, peak amplitude, and peak duration; from the SCL component, we extracted median and std parameters [31]. The HRV and EDA parameters we used are summarized in Table 2 as parameters whose performance has been universally demonstrated in stress studies [32].

TABLE 3. Questionnaire Grouping Results.

	Participants (N = 53)	Values (M ± SD)
Perceived Stress Scale		
Low perceived stress	N = 19 (35.8%)	12.05 ± 1.70
Moderate perceived stress	N = 19 (35.8%)	15.74 ± 0.85
High perceived stress	N = 15 (28.4%)	20.33 ± 2.18
Conner-Davidson Resilience Scale		
Low resilience	N = 17 (32.1%)	53.94 ± 4.58
Moderate resilience	N = 16 (30.2%)	65.19 ± 2.38
High resilience	N = 20 (37.7%)	75.00 ± 6.28

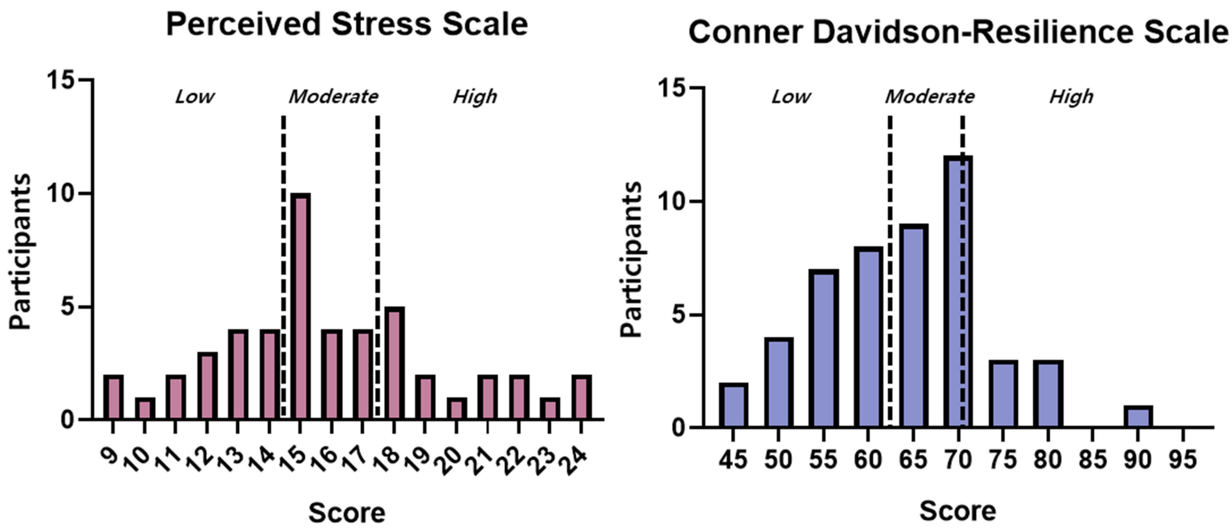


FIGURE 3. Questionnaire grouping.

TABLE 4. Analysis of EDA parameters in PSS groups.

Parameters	Low perceived stress	Moderate perceived stress	High perceived stress	Overall P-value	Post-hoc analysis P-value		
					Low vs. Moderate	Moderate vs. High	Low vs. High
Stress reactivity							
SCR std	0.324±0.137	0.245±0.131	0.209±0.096	0.006k**	0.035*	0.600	0.011*
SCR peak amplitude mean	0.394±0.181	0.295±0.200	0.242±0.130	0.022a*	0.098	0.847	0.037*
SCR peak amplitude std	0.353±0.161	0.262±0.192	0.201±0.187	0.033a*	0.158	0.763	0.044*
SCR peak amplitude max	0.158±0.567	1.200±0.722	0.941±0.492	0.004k**	0.030*	0.512	0.006**

C. STATISTICAL ANALYSIS

The participants were divided into three groups (low, moderate, high) based on their stress questionnaire scores. To analyze HRV and EDA parameters for each group during stress reactivity and recovery, the average differences in parameters per session were calculated. Changes in parameters during stress reactivity were calculated by subtracting the parameter average of the pre-resting session from the parameter average of the stress session. Changes in parameters during stress recovery were calculated by subtracting the parameter average of the stress session from the parameter average of the post-resting session. Before a statistical test, the normality of the parameters within each group was assessed by the Shapiro-Wilk test [33]. When the normality of the parameters was satisfied in all groups, we conducted one-way ANOVA tests (parametric analysis) and Kruskal-Wallis tests

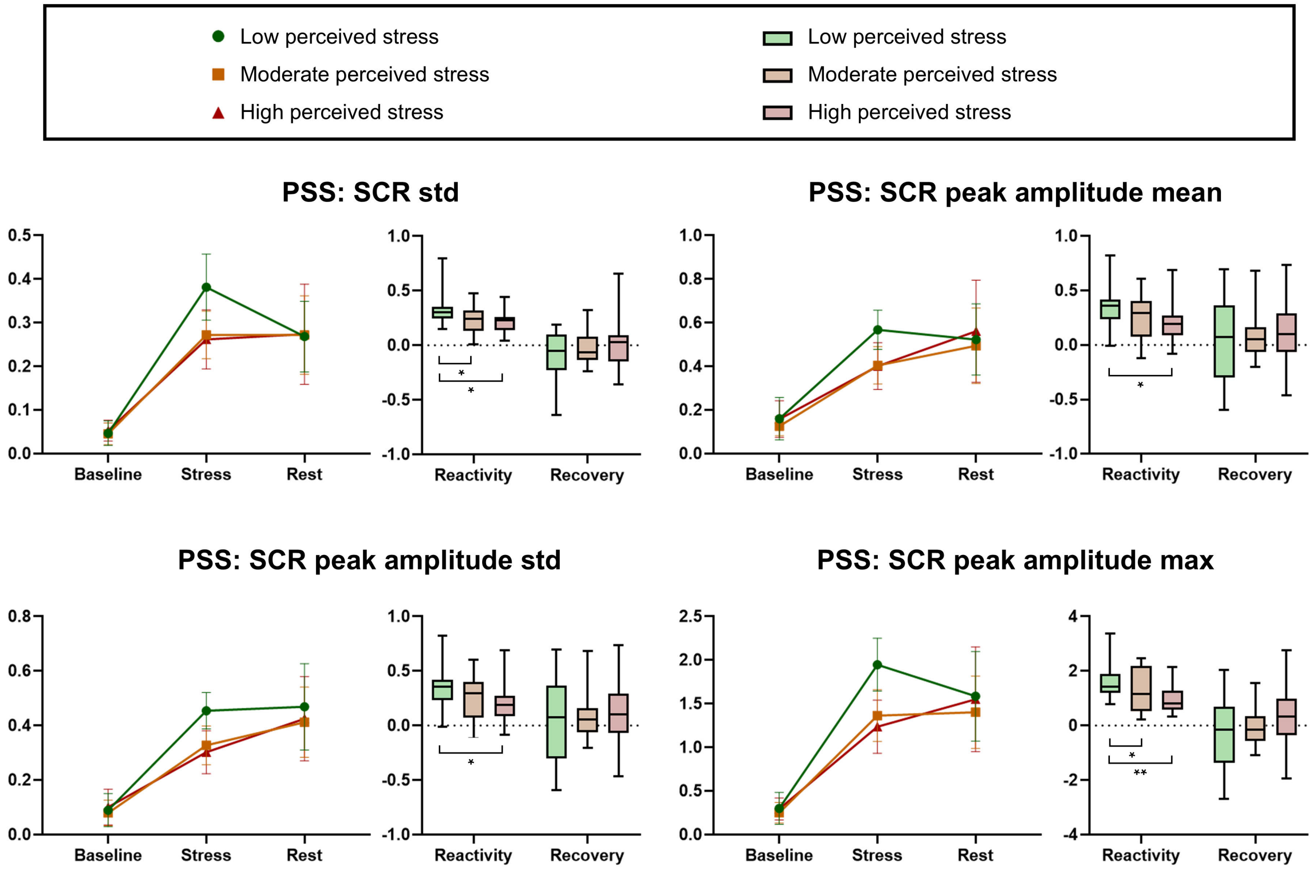


FIGURE 4. **Stress reactivity and recovery in EDA parameters.**

TABLE 5. **Analysis of HRV parameters in CD-RISC groups.**

Parameters	High resilience	Moderate resilience	Low resilience	Overall P-value	Post-hoc analysis P-value		
					Low vs. Moderate	Moderate vs. High	Low vs. High
Stress recovery							
HR	-12.46±5.27	-11.87±6.12	-7.71±5.34	0.029a*	0.109	0.952	0.043*
pNN30	-8.09±9.37	-7.59±9.85	-0.76±9.18	0.008a**	0.044*	0.963	0.008**
pNN50	-3.66±6.36	-2.31±6.37	-0.28±5.24	0.034a*	0.189	0.810	0.040*

(non-parametric analysis) [26]. For parameters that followed a normal distribution, post-hoc multiple comparisons between groups were conducted using Scheffe Post-Hoc analysis after the one-way ANOVA analysis. In cases in which data did not follow a normal distribution, post-hoc analyses between groups were performed using the Mann-Whitney test with Bonferroni correction. Statistical analyses were performed using IBM SPSS Statistics 27.

III. RESULTS

A. QUESTIONNAIRE RESULTS

A total of 53 participants were divided into three groups based on PSS or CD-RISC scores (low, moderate, high). Grouping based on tertiles resulted in PSS cutoff scores of 14 points and 17 points. Participants with PSS scores of 14 or lower were categorized into the low perceived stress group, those with scores above 14 but below 17 were placed in the moderate perceived stress group, and participants with scores higher than 17 were as-signed to the high perceived stress group. The CD-RISC cutoff scores were set at 60 points and 68 points and participants were divided into three groups (Figure 3). The characteristics of the groups are summarized in Table 3. The groups' ages showed no significant differences (PSS: $p = .526$, CD-RISC: $p = .391$). Similarly, the groups had no significant differences in marital status (PSS: $p = .777$, CD-RISC: $p = .919$) or educational level (PSS: $p = .788$,

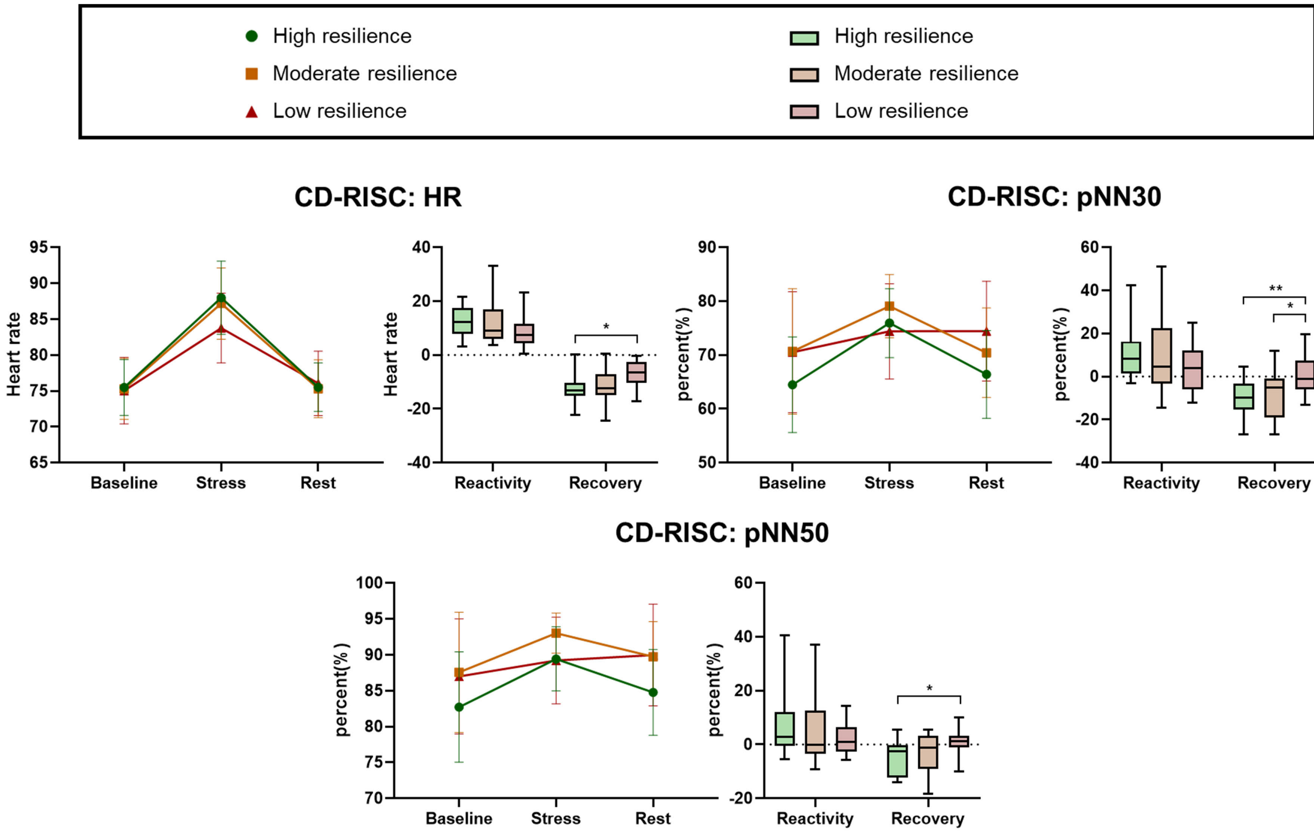


FIGURE 5. **Stress reactivity and recovery in HRV parameters.**

CD-RISC: p = 0.591). The supplementary materials detail data on biometric parameters for Baseline, Stress, and Resting protocols by group.

B. STRESS RESPONSE ANALYSIS IN PSS GROUPS

In the analysis between PSS groups, significant differences were observed in EDA parameters of SCR during the stress reactivity analysis (Table 4). SCR std ($H(2, 50) = 10.1$, $p = 0.006$), SCR peak amplitude mean ($F(2, 50) = 4.113$, $p = 0.022$), SCR peak amplitude std ($F(2, 50) = 3.672$, $p = 0.022$), and SCR peak amplitude max ($H(2, 50) = 11.087$, $p = 0.004$). Subsequent post-hoc analysis revealed significant differences among all four parameters in the low perceived stress group compared with the high perceived stress group. Additionally, differences were observed between the low perceived stress group and the moderate perceived stress group for SCR std and SCR peak amplitude max parameters. These results demonstrate a negative correlation between PSS scores and certain SCR parameters during stress reactivity (Figure 4).

C. STRESS RESPONSE ANALYSIS IN CD-RISC GROUPS

In the analysis of CD-RISC groups, significant differences were observed in HRV time domain parameters during stress recovery (Table 5). HR ($F(2, 50) = 3.814$, $p = 0.029$), pNN30 ($F(2, 50) = 5.263$, $p = 0.008$), pNN50 ($F(2, 50) = 3.614$, $p = 0.034$) showed significant differences between the groups. Post-hoc analysis of the three parameters that showed significant differences revealed statistical differences between the high resilience group and the low resilience group for all three parameters. In the case of pNN30, significant differences were also observed between the high resilience group and the moderate resilience group. As shown in Figure 5, groups with higher resilience demonstrated smoother stress recovery in HRV parameters during the rest session after the stress session. In contrast, the low resilience group showed a trend of increasing pNN30 and pNN50 parameters during the rest session without a decrease. Similar trends were observed in the other parameters, although they did not reach statistical significance. In the stress reactivity analysis between CD-RISC groups, the high resilience group showed a higher average stress response compared with the low resilience group. However, no statistically significant differences were observed between the three groups.

IV. DISCUSSION

This study analyzed physiological stress changes using the TSST protocol in healthy participants based on psychological stress factors. We recorded psychological stress factors through two questionnaires, and physiological stress responses were evaluated using physiological parameters of HRV and EDA signals during stress reactivity and stress recovery situations in the TSST protocol. The results are divided into two major categories based on the grouping of PSS and CD-RISC questionnaires. First, in the groups determined by tertile grouping of PSS questionnaire scores, we observed differences in stress reactivity between groups during stress situations, as indicated by differences in four EDA signal parameters: SCR std, SCR amplitude mean, SCR amplitude std, and SCR amplitude max. The high perceived stress group exhibited a blunted stress response compared with the low perceived stress group, with SCR std and SCR amplitude max showed differences in stress reactivity between the moderate perceived stress group and the low perceived stress group. While we observed differences among HRV parameters between PSS groups, statistically significant results were not observed. In the CD-RISC analysis, higher-resilience groups showed more remarkable stress recovery after the stress session in HRV time-domain parameters (HR, pNN30, pNN50). However, no significant differences in stress response and recovery among resilience groups based on EDA parameters were observed.

In contrast to approaches in previous studies, we conducted an integrated psychophysiological stress analysis by applying PSS and CD-RISC to analyze the physiological parameters of HRV and EDA that change during stress reactivity and recovery. The comprehensive findings of our study are broadly consistent with previous research reports. The results shown in Figure 4 support prior research indicating that continuous awareness of daily stress makes the body's stress response system less sensitive [34], [35]. The findings shown in Figure 5 support previous research indicating faster autonomic nervous system recovery after stress situations in high resilience groups [36]. A key finding of our study is that during the stress reactivity phase, EDA parameters showed more significant variability in response to perceived stress than HRV parameters. Conversely, HRV parameters are more effective tools when considering resilience and stress recovery compared with EDA parameters. These differences can be attributed to two autonomic nervous system mechanisms. First, when the body perceives stress, the hypothalamus receives direct or indirect central signals from various brain regions, activating efferent sympathetic fibers in the sympathetic nervous system. Activated efferent sympathetic fibers stimulate sweat gland secretion in the hands and feet and alter the electrical properties of the skin. EDA is a non-specific signal resulting from sweat gland activity in the skin and is solely governed by the sympathetic nervous system [37]. Therefore, EDA is suitable for analyzing stress reactivity associated with the ''fight-or-flight'' response. Second, the sympathetic nervous system becomes activated by stress, and norepinephrine (NE) binds to adrenergic receptors on cardiac cells, increasing heart rate and contractility [38]. Subsequently, as the body enters a post-resting state, the parasympathetic nervous system becomes active, maintaining the constancy of heart rate and contractility through the release of acetylcholine (ACh), which directly binds to muscarinic receptors on cardiac cells and nicotinic receptors on postsynaptic neurons [39]. HRV includes the autonomic regulation mechanism of constancy in heart rate periodic changes over time. In other words, HRV reflects the influence of the sympathetic nervous system, which reflects stress, and the parasympathetic nervous system, which reflects rest [40]. External events can activate parasympathetic nervous system responses within 1 sec, while the sympathetic nervous system responds after more than 5 sec [41] Therefore, HRV has advantages in evaluating physiological recovery due to resilience. This interpretation provides valuable information on the worth and situational applicability of physiological indicators through the relative use of HRV and EDA measures, as used in many studies. Furthermore, interpreting the body's stress response mechanisms can provide useful data for developing tools for assessing psychophysiological stress or intervention programs.

We observed no significant differences in HRV parameters among the sets of the two questionnaire groups during stress reactivity. This finding may be attributed to the characteristics of the participants. This study included healthy participants, resulting in lower average perceived stress levels compared with those in previous research participants [42]. The relatively low levels of perceived stress in the current study suggest that there was not enough discernible variation in heart rate variability (HRV) between the two questionnaire groups to capture subtle changes. However, our study provides important insights for interpreting the neurophysiological mechanisms of psychophysiological stress responses. This information was presented in a unique experimental situation that uses individual psychological characteristics. Furthermore, the stress response analysis involved 53 individuals, with each group comprising a minimum of 15 and a maximum of 20 participants. Additional research is needed to determine whether the number of individuals in each group is sufficient for generalizing physiological stress changes across groups. If a longitudinal study is conducted with more subjects in future research, the results of the questionnaire and stress reactivity and recovery can be generalized, which can be used in analyzes that remove individual differences in stress reactivity and recovery. In our study, there is a gender imbalance among participants, which reflects the demographic characteristics of the police community in South Korea. Policewomen constitute only 11.2% of the police force in Korea, a figure that closely matches the proportion of female participants recruited for our study [43], [44]. We observed that the distribution of stress parameters among female police officers within the group did not significantly influence the overall results (supplementary materials). However, future research should aim to utilize a sample with a more balanced gender ratio to evaluate these parameters more comprehensively.

A noteworthy aspect of this study is that, unlike prior research, it concurrently assessed the impact of psychological stress and resilience evaluated through the PSS and CD-RISC questionnaires on physiological stress responses and recovery. This approach may contribute to a deeper understanding of the intricate relationship between psychological stress and resilience and highlights the need for using different metrics in varying contexts. The findings of this study may aid in clarifying the understanding of psychophysiological stress responses, particularly when analyzing participants with a broader range of psychological factors in future research.

V. CONCLUSION

In this study, we analyzed the impact of individual psychological stress factors on physiological stress reactivity and recovery. We grouped 53 police officers based on their PSS and CD-RISC scores using tertiles and conducted a comparative analysis of stress re-activity and recovery using HRV and EDA parameters among the groups. The results revealed a negative correlation between perceived stress and EDA parameters and a positive correlation between resilience and HRV parameters. These results highlight the importance of understanding the relationship between psychological factors and physiological stress responses. The findings of this study may contribute to the development of personalized stress management systems and applications tailored for individuals frequently exposed to stressful environments, such as police officers, healthcare workers, and military personnel.

Future research should explore various occupational groups and the general population to validate and extend our findings. Generalizing these results can enhance therapeutic interventions aimed at improving mental health outcomes and resilience in stressed populations.

ACKNOWLEDGMENT

(Jinhak Lee and Ho Bin Hwang are co-first authors.)

REFERENCES

[1] S. Cohen, R. C. Kessler, and L. U. Gordon, "Strategies for measuring stress in studies of psychiatric and physical disorders," in *Measuring Stress: A Guide for Health Social Scientists*. New York, NY, USA: Oxford Univ. Press, 1995, pp. 3–26.

[2] D. S. Goldstein and B. McEwen, "Allostasis, homeostats, and the nature of stress," *Stress*, vol. 5, no. 1, pp. 55–58, Jan. 2002.

[3] B. Ellis, J. Jackson, and W. Boyce, "The stress response systems: Universality and adaptive individual differences," *Develop. Rev.*, vol. 26, no. 2, pp. 175–212, Jun. 2006.

[4] M. Kivimäki and A. Steptoe, "Effects of stress on the development and progression of cardiovascular disease," *Nature Rev. Cardiol.*, vol. 15, no. 4, pp. 215–229, Apr. 2018.

[5] R. A. Hackett and A. Steptoe, "Type 2 diabetes mellitus and psychological stress—A modifiable risk factor," *Nature Rev. Endocrinol.*, vol. 13, no. 9, pp. 547–560, Sep. 2017.

[6] A. Baum, M. K. O'Keeffe, and L. M. Davidson, "Acute stressors and chronic response: The case of traumatic stress," *J. Appl. Social Psychol.*, vol. 20, no. 20, pp. 1643–1654, Nov. 1990.

[7] G. E. Tafet and R. Bernardini, "Psychoneuroendocrinological links between chronic stress and depression," *Prog. Neuro-Psychopharmacol. Biol. Psychiatry*, vol. 27, no. 6, pp. 893–903, Sep. 2003.

[8] K. S. Han, L. Kim, and I. Shim, "Stress and sleep disorder," *Experim. Neurobiol.*, vol. 21, no. 4, p. 141, 2012.

[9] S. Cohen, D. Janicki-Deverts, W. J. Doyle, G. E. Miller, E. Frank, B. S. Rabin, and R. B. Turner, "Chronic stress, glucocorticoid receptor resistance, inflammation, and disease risk," *Proc. Nat. Acad. Sci. USA*, vol. 109, no. 16, pp. 5995–5999, Apr. 2012.

[10] T. Theorell, A. Hammarström, G. Aronsson, L. T. Bendz, T. Grape, C. Hogstedt, I. Marteinsdottir, I. Skoog, and C. Hall, "A systematic review including meta-analysis of work environment and depressive symptoms," *BMC Public Health*, vol. 15, no. 1, pp. 1–14, Dec. 2015.

[11] J. Campbell and U. Ehlert, "Acute psychosocial stress: Does the emotional stress response correspond with physiological responses?" *Psychoneuroendocrinology*, vol. 37, no. 8, pp. 1111–1134, Aug. 2012.

[12] A. I. Turner, N. Smyth, S. J. Hall, S. J. Torres, M. Hussein, S. U. Jayasinghe, K. Ball, and A. J. Clow, "Psychological stress reactivity and future health and disease outcomes: A systematic review of prospective evidence," *Psychoneuroendocrinology*, vol. 114, Apr. 2020, Art. no. 104599.

[13] B. S. McEwen, "Stress, adaptation, and disease: Allostasis and allostatic load," *Ann. New York Acad. Sci.*, vol. 840, no. 1, pp. 33–44, May 1998.

[14] A. T. Ginty and S. M. Conklin, "High perceived stress in relation to life events is associated with blunted cardiac reactivity," *Biol. Psychol.*, vol. 86, no. 3, pp. 383–385, Mar. 2011.

[15] L. L. Hourani, M. I. Davila, J. Morgan, S. Meleth, D. Ramirez, G. Lewis, P. N. Kizakevich, R. Eckhoff, T. Morgan, L. Strange, M. Lane, B. Weimer, and A. Lewis, "Mental health, stress, and resilience correlates of heart rate variability among military reservists, guardsmen, and first responders," *Physiol. Behav.*, vol. 214, Feb. 2020, Art. no. 112734.

[16] D. F. Tolin, E. Lee, H. C. Levy, A. Das, L. Mammo, B. W. Katz, and G. J. Diefenbach, "Psychophysiological assessment of stress reactivity and recovery in anxiety disorders," *J. Anxiety Disorders*, vol. 82, Aug. 2021, Art. no. 102426.

[17] K. von Majewski, O. Kraus, C. Rhein, M. Lieb, Y. Erim, and N. Rohleder, "Acute stress responses of autonomous nervous system, HPA axis, and inflammatory system in posttraumatic stress disorder," *Transl. Psychiatry*, vol. 13, no. 1, p. 36, Feb. 2023.

[18] S. R. de Rooij, A. H. Schene, D. I. Phillips, and T. J. Roseboom, "Depression and anxiety: Associations with biological and perceived stress reactivity to a psychological stress protocol in a middle-aged population," *Psychoneuroendocrinology*, vol. 35, no. 6, pp. 866–877, Jul. 2010.

[19] W. Linden, T. L. Earle, W. Gerin, and N. Christenfeld, "Physiological stress reactivity and recovery: Conceptual siblings separated at birth?" *J. Psychosomatic Res.*, vol. 42, no. 2, pp. 117–135, Feb. 1997.

[20] E. G. Pagès, A. Arza, J. Lazaro, C. Puig, T. Castro, M. Ottaviano, M. T. Arredondo, M. L. Bernal, R. López-Antón, C. D. L. Cámara, E. Gil, P. Laguna, R. Bailón, J. Aguiló, and J. M. Garzón-Rey, "Psychosomatic response to acute emotional stress in healthy students," *Frontiers Physiol.*, vol. 13, p. 2605, Jan. 2023.

[21] M. Tavakol and R. Dennick, "Making sense of Cronbach's alpha," *Int. J. Med. Educ.*, vol. 2, pp. 53–55, Jun. 2011.

[22] S. Cohen, T. Kamarck, and R. Mermelstein, "A global measure of perceived stress," *J. Health Social Behav.*, vol. 24, no. 4, p. 385, Dec. 1983.

[23] K. M. Connor and J. R. T. Davidson, "Development of a new resilience scale: The Connor–Davidson resilience scale (CD-RISC)," *Depression Anxiety*, vol. 18, no. 2, pp. 76–82, Sep. 2003.

[24] R. Gilgen-Ammann, T. Schweizer, and T. Wyss, "RR interval signal quality of a heart rate monitor and an ECG Holter at rest and during exercise," *Eur. J. Appl. Physiol.*, vol. 119, no. 7, pp. 1525–1532, Jul. 2019.

[25] Y. Fontein-Kuipers, M. Nieuwenhuijze, M. Ausems, L. Budé, and R. de Vries, "Antenatal interventions to reduce maternal distress: A systematic review and meta-analysis of randomised trials," *BJOG: Int. J. Obstetrics Gynaecol.*, vol. 121, no. 4, pp. 389–397, Mar. 2014.

[26] A. Kumari, A. B. H. Itagi, C. A. Rukadikar, A. D, B. N. Naik, A. Juhi, S. Naik, and S. P. Dipankar, "Effect of COVID-19 on stress and biomarkers: An exploratory cross-sectional study," *Cureus*, vol. 15, no. 3, Mar. 2023, Art. no. e35702.

[27] N. Olewuezi, "Note on the comparison of some outlier labeling techniques," *J. Math. Statist.*, vol. 7, no. 4, pp. 353–355, Oct. 2011.

[28] A. Choi and H. Shin, "Quantitative analysis of the effect of an ectopic beat on the heart rate variability in the resting condition," *Frontiers Physiol.*, vol. 9, p. 922, Jul. 2018.

[29] T. Ahmed, M. Qassem, and P. A. Kyriacou, "Physiological monitoring of stress and major depression: A review of the current monitoring techniques and considerations for the future," *Biomed. Signal Process. Control*, vol. 75, May 2022, Art. no. 103591.

[30] A. Greco, G. Valenza, A. Lanata, E. P. Scilingo, and L. Citi, "CvxEDA: A convex optimization approach to electrodermal activity processing," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 4, pp. 797–804, Apr. 2016.

[31] A. Alberdi, A. Aztiria, and A. Basarab, "Towards an automatic early stress recognition system for office environments based on multimodal measurements: A review," *J. Biomed. Informat.*, vol. 59, pp. 49–75, Feb. 2016.

[32] G. Giannakakis, D. Grigoriadis, K. Giannakaki, O. Simantiraki, A. Roniotis, and M. Tsiknakis, ''Review on psychological stress detection using biosignals,'' *IEEE Trans. Affect. Comput.*, vol. 13, no. 1, pp. 440–460, Jan. 2022.

[33] N. M. Razali and Y. B. Wah, ''Power comparisons of Shapiro-Wilk, Kolmogorov–Smirnov, Lilliefors and Anderson-Darling tests,'' *J. Stat. Model. Anal.*, vol. 2, no. 1, pp. 21–33, 2011.

[34] W. T. Boyce and E. Chesterman, ''Life events, social support, and cardiovascular reactivity in adolescence,'' *Pediatric Res.*, vol. 11, no. 3, pp. 105–111, 1990.

[35] D. Carroll, A. C. Phillips, C. Ring, G. Der, and K. Hunt, ''Life events and hemodynamic stress reactivity in the middle-aged and elderly,'' *Psychophysiology*, vol. 42, no. 3, pp. 269–276, May 2005.

[36] R. Codonhato, J. R. N. Vissoci, J. R. A. D. Nascimento Junior, M. V. Mizoguchi, and L. Fiorese, ''Impact of resilience on stress and recovery in athletes,'' *Revista Brasileira de Medicina do Esporte*, vol. 24, no. 5, pp. 352–356, Sep. 2018.

[37] C. Tronstad, M. Amini, D. R. Bach, and Ø. G. Martinsen, ''Current trends and opportunities in the methodology of electrodermal activity measurement,'' *Physiolog. Meas.*, vol. 43, no. 2, Feb. 2022, Art. no. 02TR01.

[38] J. A. Armour, ''Cardiac neuronal hierarchy in health and disease,'' *Amer. J. Physiol.-Regulatory, Integrative Comparative Physiol.*, vol. 287, no. 2, pp. R262–R271, Aug. 2004.

[39] T. A. Johnson, A. L. Gray, J.-M. Lauenstein, S. S. Newton, and V. J. Massari, ''Parasympathetic control of the heart. I. an interventriculo-septal ganglion is the major source of the vagal intracardiac innervation of the ventricles,'' *J. Appl. Physiol.*, vol. 96, no. 6, pp. 2265–2272, Jun. 2004.

[40] G. Ernst, ''Heart-rate variability—More than heart beats?'' *Frontiers Public Health*, vol. 5, p. 240, Sep. 2017.

[41] D. Nunan, G. R. H. Sandercock, and D. A. Brodie, ''A quantitative systematic review of normal values for short-term heart rate variability in healthy adults,'' *Pacing Clin. Electrophysiol.*, vol. 33, no. 11, pp. 1407–1417, Nov. 2010.

[42] D. K. Chatkoff, K. J. Maier, and C. Klein, ''Nonlinear associations between chronic stress and cardiovascular reactivity and recovery,'' *Int. J. Psychophysiol.*, vol. 77, no. 2, pp. 150–156, Aug. 2010.

[43] J. L. Kim, W. Wells, J. J. Vardalis, S. K. Johnson, and H. Lim, ''Gender difference in occupational stress: A study of the South Korean national police agency,'' *Int. J. Law, Crime Justice*, vol. 44, pp. 163–182, Mar. 2016.

[44] K. N. P. Agency. (2024). *Statistics Data*. Korean Nat. Police Agency. Accessed: May 17, 2024. [Online]. Available: https://www.police.go.kr/www/open/public/public0208.jsp

JINHAK LEE received the B.S. degree from the Department of Biomedical Engineering, Yonsei University, South Korea, in 2022. He is currently pursuing the M.S. degree in biomedical engineering with Hanyang University, South Korea. His current research interests include wearable devices, bio-signal analysis, machine learning, and stress assessment based on questionnaires and bio-signal.

HO BIN HWANG received the B.S. degree from the Department of Biomedical Engineering, Yonsei University, South Korea, in 2020, and the M.S. degree in biomedical engineering from Hanyang University, South Korea, in 2022, where he is currently pursuing the Ph.D. degree in biomedical engineering. His current research interests include wearable devices-based bio-signal analysis, bio-crypto systems, and ECG-based biometrics.

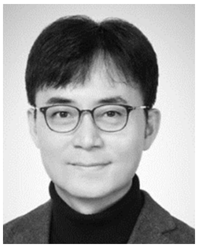
SEUNGJAE LEE received the B.S. degree from the Department of Biomedical Engineering, Yonsei University, South Korea, in 2015, and the Ph.D. degree in biomedical engineering from Hanyang University, South Korea, in 2022. His current research interests include biomedical measurement systems, human motion analysis, and stress assessment based on heart rate variability analysis.

JAYON KIM received the B.S. degree from the Department of Bio-Environmental Chemistry, Wonkwang University, in 2018, and the M.S. degree from the Department of Anatomy and Cell Biology, Hanyang University, in 2022, where she is currently pursuing the Ph.D. degree. Her research interest includes functional and neuroanatomical changes in CNS structures related to stress situations.

JEYEON LEE received the Ph.D. degree in biomedical engineering from Hanyang University, in 2017. Following the Ph.D. study, he was a Postdoctoral Fellow and an Assistant Professor with the Mayo Clinic, from 2017 to 2023. He is currently an Assistant Professor with the Department of Biomedical Engineering, College of Medicine, Hanyang University. His research interests include developing a digital healthcare system as a clinical decision support tool, particularly using neuroimaging and electrophysiology data.

SANGHAG KIM received the Ph.D. degree in sociology from The University of Iowa. He was a Research Associate with the Department of Psychological and Brain Sciences, The University of Iowa. He is currently a Professor with the Department of Sociology, Hanyang University. He has published articles in journals, such as *Child Development*, *Development and Psychopathology*, and *Population and Development Review*. His research interests include social psychology, human development and socialization, values and morality, and the quality of life and happiness.

JUNG HEE HA received the B.S., M.A., and Ph.D. degrees from the Department of Education, Hanyang University, South Korea, in 1996, 1998, and 2005, respectively. She was an Assistant Professor with the Department of Counseling Psychology, Hanyang Cyber University, from 2009 to 2015. She has been a Professor with the Graduate School of Counseling Psychology, Hanyang University, since 2016. Her current research interests include multicultural counseling, adolescent adaptation, and perfectionism.



YOOJIN JANG received the B.S. and M.A. degrees from the Department of Education, Hanyang University, South Korea, in 1997 and 1999, respectively, and the Ph.D. degree in counselor education from The University of Iowa. He has been a Professor with the Graduate School of Counseling Psychology, Hanyang University, since 2016. His research interests include counseling supervision, multicultural counseling, and mental fitness training.

SEJIN HWANG received the B.S. degree from the Department of Medicine, Hanyang University, South Korea, in 1987, and the M.S. and Ph.D. degrees in anatomy from Hanyang University, in 1989 and 1995, respectively. He has been a Professor with the Department of Anatomy and Cell Biology, Hanyang University, since 1995. His research interest includes functional and neuroanatomical changes in CNS structures related to stress situations.

HOON-KI PARK received the M.D. degree from the College of Medicine, Seoul National University, South Korea, in 1987. Since 1995, he has been a Professor with the Department of Family Medicine, College of Medicine, Hanyang University. His research interests include biomedical signal applications, medical education, and the training of primary care physicians. He is the Director of the Educational Committee, Korean Academy of Family, and a Committee Member of Korean Medical Licensing Examination.

JONGSHILL LEE received the B.Sc., M.Sc., and Ph.D. degrees in electronic engineering from Inha University, Incheon, South Korea, in 1995, 1997, and 2005, respectively. From 2001 to 2005, he was a Lecturer with the Department of Electronic Engineering, Korea Polytechnic University, Siheung, South Korea, where he was engaged in research on digital signal processing and digital image processing. He is currently a Research Professor with the Department of Biomedical Engineering, Hanyang University, Seoul, South Korea. His research interests include wearable devices, gait measurement and analysis, biometric authentication, cardiovascular systems, and wearable sensors (IMUs, PPG, and ECG). He is a Guest Editor and a Topical Advisory Panel Member of the journal *Sensors*.

IN YOUNG KIM received the B.S. degree from the College of Medicine, Seoul National University, South Korea, in 1989, and the M.S. and Ph.D. degrees in biomedical engineering from Seoul National University, 1991 and 1994, respectively. He was the Principal Investigator with the Samsung Biomedical Research Institute, South Korea, from 1994 to 1997. From 1998 to 2000, he was a Senior Researcher with the Samsung Advanced Institute of Technology. Since 2000, he has been with the Department of Biomedical Engineering, Hanyang University, South Korea, as a Professor. He has published more than 350 technical articles in peer-reviewed international journals and has 48 issued patents. His current research interests include bio-signal analysis, disease diagnosis using deep learning, and non-invasive vagus nerve stimulation.