The Effect of Noise Sensitivity on Psychophysiological Response Through Virtual Reality Environment Experience: A Randomized Control Trial

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Abstract

Noise sensitivity is a crucial factor affecting subjective psychophysiological responses to the acoustic environment of various indoor and outdoor spaces. This study examines how noise sensitivity or hyperacusis affects emotional recovery and recovery of the autonomic nervous system (ANS) response in experiencing various environments (urban and natural) of virtual reality (VR) that represents the actual environment. A total of 60 general participants with mild depression, stress, and anxiety were examined using a survey to investigate individual characteristics, including noise sensitivity, and used K-means clustering to classify the sensitivity groups. Emotional responses were measured using the Korean edition of Profile of Mood States and physiological responses were measured by assessing heart rate variability. Overall, the emotional recovery effect was greater in the natural environment than the urban environment, and the homeostatic mechanism of the ANS was better maintained, thereby increasing stress resistance. We discovered that noise sensitivity does not have much effect on psychophysiological recovery in the natural environment, but has a significant effect on emotional response in the urban environment. This can be used as basic data in seeking customized emotional recovery for individuals using VR technology in the future.

1. Introduction

In general, groups with high noise sensitivity are likely to show greater annoyance to noises that occur inside and outside various spaces [1]. Noise sensitivity refers to the subjective response to noises and is known to be one of the personality traits of individuals [2]. Individual responses to noises may vary depending on non-acoustical factors such as individual personalities, attitudes toward noises, previous experiences, exposure to the noise environment, and acoustical factors such as sound pressure, noise level, and frequency characteristics [3]. Therefore, to explain noise sensitivity, it is necessary to consider the characteristics of the noise itself and various non-acoustical factors that affect individual responses.

There are various subjectively unpleasant noise sources such as the door slamming, phone ringing, water running, cooking sounds, and voices. Some of the most common noises include traffic noises, vacuum cleaners, kitchenware and workshop noises, drilling, dishes clanking, and children yelling [4, 5]. However, some people also experience earache, dizziness, anxiety, tension, startle response, and panic attacks due to common sound stimuli.

These individual characteristics related to noise sensitivity can be explained by hyperacusis, commonly defined as “a disorder that makes it hard to deal with everyday sounds that others generally do not find uncomfortable.” It refers to a diminished sound tolerance from being too loudness dependent than others due to oversensitive hearing. Thus, the loudness discomfort level is lower than normal [6].

Hyperacusis also refers to hyperacute or super-normal hearing or a lowered hearing threshold. However, this is extremely rare in clinical practice and is observed when the superior semicircular canal dehiscence exposes a negative bone-conduction hearing threshold [7]. In sum, it generally refers to the downward

shift of the hearing threshold or loudness discomfort level of the dynamic hearing range due to abnormal auditory gain. People with low loudness discomfort levels may show slower recovery of emotional discomfort caused by noises than others. Hyperacusis indicates a hypersensitivity to loudness levels where abnormally strong auditory cues occur in most frequency bands. Alternatively, phonophobia or misophonia refers to the avoidance of certain sounds due to discomfort and pain. It is usually accompanied by autonomic nervous system (ANS) responses (cold sweat, palpitation) like limbic system responses (irritation, pain, fear, avoidance) [8].

Meanwhile, with the recent emergence of virtual reality (VR) technology, various attempts have been made to promote psychophysiological recovery effect through the VR environment experience [9–14]. Studies generally concluded that experiences in natural environments like the forest or urban park positively affect the psychophysiological recovery of humans. Some studies [12] discovered the possibility of potential recovery in natural and urban environments. However, there is insufficient research examining how the difference in individual noise sensitivity affects psychophysiological recovery. Park et al. [15] examined the difference in recovery response of VR environment experiences due to noise sensitivity. However, they failed to discover a clear difference due to limited stimuli and short experience time. Thus, the correlation between noise sensitivity and psychophysiological response is yet to be found.

Therefore, this study examines how hyperacusis affects emotional and ANS responses recovery in various environments (urban and natural) using VR that represents the real environment.

2. Methods

2.1 Audio-visual stimuli

As shown in Figure 1, we selected nine sites in Korea that represent urban and natural spaces. Typical places where urban residents spend most of their time were selected as urban spaces. These places include high-density and low-density commercial and business areas. Natural spaces were classified into waterfront and green spaces. The river, wetland, and ocean were selected as waterfront spaces, and the valley, forest, and temple were included in green spaces. In this study, we attempted to create an environment like the actual sites in a lab setting using VR technology [12, 16]. To this end, audio-visual stimuli necessary for creating the VR environment were collected from the selected sites. Measurements were conducted during the daytime in May 2020. Visual information was recorded using a 6-channel 360-degree camera (Insta 360 pro, Insta 360), and audio information was recorded by connecting a 4-channel ambisonic microphone (Soundfield SPS 200, Sound field Ltd.) to a portable sound recorder (Mixpre-6, Sounddevices). Here, a separate calibration microphone was used to calibrate the same sound pressure level as the actual sites in lab settings. All measurements were collected for three minutes at 1.6 m, human eye level from a fixed position.

2.2. VR environment

This study created an experience environment in lab settings using VR technology based on previous studies [17–20]. The VR environment was created using Unity 3D software, and visual information was obtained by stitching 6-channel videos into one 360-degree video. Then, we obtained audio information by converting the A-format first-order ambisonic sound source into B-format first-order ambisonic. Then, we down-mixed it into two channels using a spatial audio software development kit (SDK), creating three minutes of audio-visual stimulation sound source for each point. For the edited audio-visual information, visual information was provided through a head-mounted display (HMD, VIVE Pro, HTC), and audio information was provided through open-type headphones (HD-650, Sennheiser). Here, the direction of sound from the head rotation was implemented in real-time using the embedded head-tracker on HMD. Moreover, the sound pressure level of the sound sources played on headphones was adjusted to be equivalent to that of the sound sources recorded using the calibration microphone.

2.3 Experimental design

2.3.1. Participants

The study's participants were ordinary people with mild depression, stress, and anxiety. To minimize variations in responses, participants were limited to students enrolled in a university or graduate school who had a routine lifestyle with similar daily patterns (mean age = 24.3, standard deviation = 2.4). The assessment included 60 participants with normal levels of sight and hearing. As shown in Table 1, most participants showed high stress levels at 19 points or higher. Additionally, some showed high depression at ten points or higher, proving that the participants recruited in this study usually had an active need for emotional recovery. There was a wide distribution of noise sensitivity, personality, temperament, and life satisfaction. This indicated that the 20s were sufficiently representative.

Table 1
Summary of demographical and health conditions of participants.

Parameter	Mean (SD)	Min	Max
Age (number)	24.3 (2.4)	21	30
<i>Male (30)</i>	25.5 (2.3)	21	30
<i>Female (30)</i>	23.2 (1.9)	21	28
Health condition (number)			
Patient Health Questionnaire (PHQ-9)	3.9 (3.2)	0	14
<i>PHQ-9 0 – 4 (39)</i>	2.0 (1.5)	0	4
<i>PHQ-9 5 – 9 (17)</i>	6.2 (1.4)	5	9
<i>PHQ-9 10 – 19 (4)</i>	11.8 (1.7)	10	14
State-Trait Anxiety Inventory (STAI-Y)	20.3 (5.3)	8	34
Perceived Stress Scale (PSS)	21.7 (4.2)	12	30
<i>PSS 0 – 12 (3)</i>	12.0 (0.0)	12	12
<i>PSS 13 – 15 (1)</i>	14 (0.0)	14	14
<i>PSS 16 – 18 (7)</i>	17.3 (0.0)	16	18
<i>PSS 19 – 40 (49)</i>	23.0 (3.1)	19	30
Noise sensitivity	79.1 (16.1)	45	112
Hyperacusis	11.4 (6.6)	1	26
Temperament and character dimension			
Novelty Seeking (NS)	58.5 (10.0)	40.0	88.0
Harm Avoidance (HA)	49.4 (12.2)	22.0	73.0
Reward Dependence (RD)	54.9 (13.9)	23.0	89.0
Persistence (P)	51.4 (10.7)	31.0	75.0
Self-Directiveness (SD)	51.6 (11.2)	17.0	77.0
Cooperativeness (C)	49.8 (13.4)	1.0	77.0
Self-Transcendence (ST)	46.8 (9.2)	29.0	70.0
Quality of life (WHOQOL-BREF)			
Total score	68.9 (8.9)	42.8	86.6

2.3.2. Questionnaires

The questionnaire consisted of five parts. 1) Demographic information such as gender and age of participants was collected. 2) To examine sound sensitivity and the usual health state, we investigated nine items of the patient health questionnaire (PHQ-9), 20 items of the state-trait anxiety inventory (STAI-Y), ten items of the perceived stress scale (PSS), 21 items on noise sensitivity [21], and 14 items on hyperacusis [22]. 3) To assess individuals' usual personality and temperament, 140 items of the Temperament and Character Inventory-Revised Short Version (TCI-RS) [23] were assessed. 4) To examine life satisfaction, 26 items of the World Health Organization Quality of Life Questionnaire (WHOQOL-BREF) [24] were investigated. 5) 65 items of the Korean edition of Profile of Mood States (K-POMS) [25] were investigated to examine the psychological recovery response to each VR environment.

2.3.3. Heart rate variability responses

Heart rate variability (HRV) was measured to investigate participants' physiological responses during the VR environment experience. HRV shows the periodic change in heart rate over time and is closely related to the interaction between sympathetic and parasympathetic nerves. SA-3000NEW (Medicore, Korea) was used for measurement, and the sensor was attached to the inner side of the wrists and ankles of participants to measure HRV for three minutes. Five indicators were selected, and the results were quantified into means of three minutes: 1) heart rate (HR) indicating the average heartbeat for one minute, 2) total power indicating the vitality of ANS, 3) standard deviation of normal to normal (SDNN) indicating stress resistance, 4) temporary stationarity index representing stress, and 5) low frequency was used as an index for sympathetic nerve activity and indicated fatigue. The HRV response was obtained by calculating the relative difference (%)¹ instead of the absolute value of the measures, using the formula $\frac{(\text{raw value} - \text{stress-state value})}{\text{stress-state value}} \times 100$. Here, physiological responses when experiencing VR stimuli were used as raw values. Errors in physiological responses among individual participants were minimized through this normalization process.

2.3.4. Stress task

We provided computerized mental arithmetic tasks (MAT) to induce participants' stress before the VR environment experience. Mental subtraction problems were shown for one second to the participants in the VR environment, which they were to solve in three seconds. When they gave incorrect answers, they were to repeat the same problem from the beginning, thereby inducing a stress reaction.

2.3.5. Procedure

Simple education was provided before the experiment about the purpose of this study and the questionnaire. This was done to ensure that the participants sufficiently understood the meaning of the questionnaire and items. The research proposal was approved by the Institutional Review Board as an ethical procedure (HYUIRB-202010-011). The protocol was performed in accordance with the relevant guidelines and regulations. The informed written consent was also received from each participant. The participants were explained how their responses would be used, processed, and stored. We recommended that they sleep and rest the day before the experiment. They were also not allowed to consume caffeine, smoke, or take medication that may change their physiological response the day of the experiment and

the day before. Moreover, the participants wore light clothing without their coats. A simple training session was included to allow those unfamiliar with a VR device to adjust to the environment.

Before the VR assessment, the participants put on HRV measuring hardware, HMD, and headphones, before calibration of each device. To set the baseline (reference) standard, HRV responses were collected for three minutes each in the state of stress task and no stimuli. In addition, K-POMS responses were collected in the state of no stimuli. Next, HRV responses were collected for three minutes each in the state of stress task and VR stimuli in the main experiment. After the stimuli experience, K-POMS responses were collected. Considering the participants' fatigue due to the experiment's length, each participant was given three stimuli (one for the function of each space) randomly selected out of nine stimuli. In other words, each participant experienced one of the urban spaces, waterfront spaces, and green spaces. They were given breaks during the experiment, as needed, to minimize their fatigue or discomfort. Responses of 20 participants were obtained at each assessment site; thus, 180 results ($9 \text{ sites} \times 20 \text{ responses}$) were collected for each assessment item. All survey responses were given using the controller in the VR environment.

2.4 Data analysis

The following analyses were conducted using SPSS Statistics (IBM, version 25). All responses were tested for normality (Shapiro-Wilk and Kolmogorov-Smirnov) and homoscedasticity (Levene). The data satisfied normality, and thus parametric statistics were conducted. Analysis of variance was conducted to examine whether there is a statistically significant difference in K-POMS responses and HRV responses depending on the function of the space. K-means clustering was used to classify the participants by individual health state, including hyperacusis. Additionally, a t-test was conducted to determine the significance of the difference in psychophysiological responses between the groups.

3. Results

Cluster analysis was conducted to classify 60 participants based on their health state. We used the K-means clustering method known to be efficient and applicable to various types of data. Five indicators (PHQ-9, STAI-Y, PSS, noise sensitivity, hyperacusis) were used as independent variables. Since there were five independent variables, Minkowski distance was used, which is suitable for at least two-dimensional data as a subjective measure for similarity among participant responses.

It is necessary to determine the number of clusters in advance for K-means clustering, and the results vary depending on that number. Thus, the verification process was conducted using "NbClust" package² provided by R language to set the optimal number of clusters. As shown in Table 2, the number of clusters was determined based on 26 indices. As a result, clusters were classified into two clusters recommended by 12 out of 26 indices. Thus, 28 participants were classified into Cluster 1, and 32 into Cluster 2.

Table 2
Twenty-six index values for determining the optimal number of clusters

Methods	Index	Year	Authors	N	Index value
Maximum / Minimum value of the index	CH	1974	Calinski and Harabasz	2	76.7
	Dunn	1974	Dunni	4	0.2
	McClain	1975	McClain and Rao	2	0.5
	Cindex	1976	Hubert and Levin	10	0.4
	DB	1979	Davies and Bouldin	2	0.9
	Ptbiserial	1980	Millian	2	0.6
	CCC	1983	Sarle	2	19.7
	Silhouette	1987	Rowsseeuw and Lai	2	0.4
	KL	1988	Krzanowski and Lai	9	48.5
	SDindex	2000	Halkidi et al.	2	0.2
	SDbw	2001	Halkidi and Vazirgiannis	10	0.1
Maximum difference between hierarchy levels of the index	Ball	1965	Ball and Hall	3	2196.9
	Friedman	1967	Friedman and Bubin	0	0.0
	Scott	1971	Scott and Symons	4	45.3
	Hartigan	1975	Hartigan	4	8.7
	Ratkowsky	1978	Ratkowsky and Lance	2	0.3
	TrCovW	1985	Milligan and Cooper	3	2.4×10^6
Etc.	Rubin	1967	Friedman and Rubin	9	-8.6
	Beale	1969	Beale	2	-0.5

Methods	Index	Year	Authors	N	Index value
	Marriot	1969	Marriot	2	4.6×10^{15}
	Frey	1972	Frey and Van Groenewoud	4	1.4
	Pseudot2	1973	Duda and Hart	2	-7.0
	Duda	1973	Duda and Hart	2	1.2
	TraceW	1985	Miligan and Cooper	10	269.6
	Hubert	1985	Hubgert and Arobie	4	898.2
	Dindex	2000	Lebart et al.	0	0.0

Principle component analysis was conducted on the five cases of health data, and the distribution of Cluster 1 and Cluster 2 is provided in Figure 2 based on the results. Varimax rotation was applied here. The statistical model was significant with Kaiser-Meyer-Olkin's measure of sampling adequacy below 0.564 and Bartlett's test of sphericity below 0.05. Factor 1 had the explanatory power of 43.4% and showed high sensitivity (loading = 0.919), hyperacusis (loading = 0.854), and STAI-Y (loading = -0.173), thereby representing sensitivity to the sound environment. Factor 2 had the explanatory power of 22.4% and was highly correlated with PHQ-9 (loading = 0.907) and PSS (loading = 0.856), thereby representing the state of emotional difficulty. As a result, Group 1 and Group 2 were clearly divided based on the standard of factor 1.

Table 3 compares the differences in demographic and health conditions between the two groups based on the previously examined standard. A t-test was conducted to test the statistical significance of the mean difference between the two groups; this is presented in Table 3. As a result, characteristics values excluding noise sensitivity and hypersensitivity (gender, age, depression, anxiety, stress, personality, life satisfaction) did not show a significant difference. Therefore, Group 1 was relatively less sensitive to sound than Group 2, they can be defined as the low and high noise-sensitive group, respectively.

Table 3
Difference of demographic and health condition according to different groups

Methods	Group 1	Group 2	t	P-value	95% CI of the diff.	
					Lower	Upper
Gender	Number	Number				
Male	16	14				
Female	12	18				
Year	Mean (SD)	Mean (SD)				
Age	24.1 (2.5)	24.6 (2.3)	-0.80	.43	-1.72	0.74
Health condition						
PHQ	3.4 (3.4)	4.2 (3.0)	-0.96	.34	-2.45	0.87
STAI-Y	21.2 (4.7)	19.5 (5.8)	1.20	.24	-1.11	4.41
PSS	21.0 (4.0)	22.2 (4.3)	0.26	.26	-3.37	0.94
Noise sensitivity	64.5 (8.6)	91.8 (8.4)	-12.45	<.01	-31.67	-22.89
Hyperacusis	7.4 (5.0)	14.9 (5.7)	-5.40	<.01	-10.35	-4.75
Temperament and character dimension						
Novelty Seeking (NS)	58.4 (10.1)	58.7 (10.1)	-0.13	.90	-5.54	4.88
Harm Avoidance (HA)	46.6 (10.5)	51.9 (13.2)	-1.70	.10	-11.48	0.95
Reward Dependence (RD)	53.7 (13.1)	55.9 (14.8)	-0.60	.55	-9.41	5.09
Persistence (P)	53.1 (11.4)	49.9 (9.9)	1.19	.24	-2.23	8.77
Self-Directiveness (SD)	54.1 (10.1)	49.5 (11.9)	1.61	.11	-1.13	10.34
Cooperativeness (C)	50.7 (13.2)	49.1 (13.7)	0.46	.64	-5.36	8.59
Self-Transcendence (ST)	46.1 (9.4)	47.4 (9.1)	-0.53	.60	-6.06	3.52
Quality of life (WHOQOL-BREF)						
Total score	71.0 (8.3)	67.1 (9.2)	1.70	.10	-0.70	8.41

Emotional recovery responses through VR stimuli experience were examined through K-POMS, and the results are as shown in Figure 3. They were classified into eight measures: Tension-Anxiety (TA), Depression-Dejection, Anger-Hostility (AH), Vigor-Activity (AH), Fatigue-Inertia (VA), Confusion-Bewilderment (CB), Friendliness (FR), and Total Mood Disturbance (TMD). Figure 3 (a) shows the emotional changes depending on the function of space. Compared to the reference value, negative emotional responses increased slightly overall in the urban environment, while they decreased with

statistical significance in the natural environment. In terms of emotional change in the reference and the city, there was a slight increase in negative responses but not with statistical significance. This is because, since the participants are mostly familiar with the city, they did not have much resistance or negative views about the urban environment. As for the emotional difference between urban and natural environments, negative emotional responses such as AH, FI, CB, and TMD were lower in nature, indicating that the natural environment created in VR had a psychologically positive effect on the participants.

The results of analyzing the two groups depending on noise sensitivity are presented in Figure 3 (b) – (e) by the function of space. As shown in Figure 3 (b), there was a significant difference in emotional responses between the two groups in the city. Group 2 (high noise-sensitive group) showed higher TA, FI, and TMD than Group 1 (low noise-sensitive group) by 3.97, 0.52, and 16.50, respectively. On the other hand, there was no significant difference in waterfront and green areas between the two groups in the natural environment.

Physiological recovery responses through VR stimuli experience were examined with HRV, and the results are shown in Figure 4. First, Figure 4 (a) shows the changes in HRV depending on the function of space as did in the results of emotional responses previously examined. The results showed that HR increased by 7.24, 6.64, and 8.42% each from the reference in all urban, waterfront, and green spaces with statistical significance. Moreover, SDNN increased by 14.70 and 14.74% in waterfront and green spaces than the reference with statistical significance. SDNN refers to how irregular and complicated HRV was during recording time. Irregular HR indicates that the homeostatic mechanism of the autonomic nervous system is working properly, and that the coping skills for various stressors are being improved. Therefore, like the emotional responses that are previously examined, we found that the natural environment created in the VR environment can bring a physiological recovery effect to the participants even in physiological responses. Next, the results of the two groups by noise sensitivity are provided in Figure 4 (b) – (e) depending on the function of space. Unlike the emotional responses, there was no significant difference between the two groups in physiological responses.

4. Discussion

This study examined whether noise sensitivity or hyperacusis affects emotional and ANS response recovery using VR. The results showed that the group with low noise sensitivity experienced relatively more positive emotions in the natural environment created in VR.

Hyperacusis is a disease that can be explained by integrating multifactorial causes and hypotheses as “abnormal auditory gain.” In other words, abnormally excessive neural excitement occurs compared to the loudness of the sound input [28]. Hyperacusis mostly indicates decreased sound tolerance and sometimes the decline of the hearing threshold, that is, abnormally excellent hearing. Various illnesses can cause the two symptoms, but they can occur when there is excessive auditory gain due to a disorder in the auditory gain control mechanism. In this study, the group with relatively high noise sensitivity may

have slowed down the emotional recovery due to more neural excitement than recovery due to the natural environment stimuli.

Changes in afferent neural plasticity, neurotransmitter, hormones, and olivocochlear efferent control disorder have been studied as the pathological mechanisms of the central auditory system related to hyperacusis, leading to an abnormal increase in auditory gain (number of neural signals generated). The sounds in the natural environment as the common relaxation stimulus in excessive signals are correlated to the increase in overall neural signals, thereby contributing to negative emotions rather than the relaxation effect.

It may be most effective to use a survey to verify individual responses to negative sound stimuli in the environment and investigate positive/negative emotions, damages, and responses to various environmental noises. However, there may be a difference in response to noise depending on individual traits about noise sensitivity. Surveys can be conducted on large samples with relatively low cost and time. The responses may still be affected by complex factors other than specific factors that the researcher intended to investigate [29].

Accordingly, the psychoacoustic experiment can be used, which quantifies the noise sensitivity of respondents. The psychoacoustic experiment requires much cost and time, affecting sample size, but other factors can be controlled under lab conditions, and clear responses to certain noise sources can be observed [29]. The lab where the psychoacoustic experiment is conducted, because the experiment must be under controlled conditions, may seem like a strange place to the participants. Thus, forming the experiment so that the space can be perceived as comfortable and relaxing for the participants is also an important procedure for increasing the reliability of measured data [29].

The same environmental stimuli can be given in the controlled environment by using the VR environment. The group with high noise sensitivity in previous studies on indoor noise sensitivity using VR reported higher annoyance when the sound comes from the outside [30]. For the group with low noise sensitivity, external noise has a 'masking effect' over internal noise. In contrast, external noise may have a 'moderating effect' that increases discomfort toward internal noise for the group with high noise sensitivity. For the participants sensitive to noise, recognition of the negative acoustic environment due to exposure to external noise may have affected the recognition of internal noise [30].

This study assessed emotional recovery responses through VR stimuli experienced by dividing participants into a control group and a hyperacusis group. The hyperacusis group showed significantly high TA, FI, and TMD in the urban environment. Thus, there was a significant difference in emotional responses between the two groups only in the urban environment. The emotional difference due to noise sensitivity may have been more apparent in urban environment than the natural environment that is relatively fixed since the city has various noise sources (road traffic noise, construction noise, noise caused by human activities, music, etc.). Therefore, clustering based on noise sensitivity and hyperacusis in this study may have been a significant method in examining the emotional differences in urban environments.

The limitations of this study are as follows. First, only subjective assessment results were used for clustering based on noise sensitivity. However, responses within individuals were made consistent through the controlled experiment using the VR environment in the same settings. Second, while the participants were classified by noise sensitivity, they were not patient groups with hyperacusis. It is necessary to check whether the results of this study can be reproduced using clinical patients with hyperacusis. Third, no difference was found between the two groups in the HRV tests to check the actual physiological change. This may be because HRV measurement failed to closely reflect change due to the relatively short experiment. It is also necessary to track and verify the effect of the recovery environment over a long period.

Nonetheless, this study provided stimuli using the controlled VR environment. It assessed the emotional states in advances such as anxiety, subjective stress, and depression, showing no difference in emotional pathology between groups. Negative emotions such as depression and anxiety are both the cause and effect of hyperacusis. However, we controlled this in advance and could check the group characteristics based on pure noise sensitivity differences. Further research is needed on clinical patients with hyperacusis to determine whether actual noise sensitivity affects emotional and environmental recovery. Moreover, it is necessary to verify whether this short-term emotional recovery effect is maintained continuously through long-term tracking and monitoring.

This study examined how experiences of urban and natural environments created by VR technology affect the recovery of emotional and ANS responses of normal people with mild depression, anxiety, and stress. Overall, the participants showed higher emotional and ANS recovery responses in the natural environment than in the urban environment. Moreover, the recovery difference was not significant in the waterfront and green spaces. There was a difference in psychophysiological response between groups depending on noise sensitivity only in the urban environment. Therefore, noise sensitivity was proved to be a critical factor that must be considered when investigating emotional responses in the urban environment. This discovery can be used as basic data for creating personalized VR recovery contents considering the individual characteristic of noise sensitivity in developing various contents to promote psychophysiological recovery of humans through VR experience.

Declarations

Data Availability

Supporting data will be made available to Editorial Board Members and referees at the time of submission for the purposes of evaluating the manuscript.

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Author Contributions

Conceptualization, K.L., J.Y.J. and H.I.J.; Formal analysis, H.I.J.; Funding acquisition, J.Y.J.; Investigation, H.I.J.; Methodology, H.I.J.; Project administration, J.Y.J.; Supervision, J.Y.J.; Visualization, H.I.J.; Writing - original draft, H.I.J.; Writing - review & editing, H.I.J., J.Y.J., K.L.

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Competing Interests

The authors declare no competing interests.

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Figures

Figure 2

Cluster analysis results based on health conditions. Group 1 represents low noise-sensitive, and Group 2 represents high noise-sensitive.

Figure 3

Difference of the Korean edition of Profile of Mood States (K-POMS) between before and during VR stimuli experience. (a) K-POMS difference according to space function, (b) K-POMS difference in reference with different groups, (c) K-POMS difference in urban with different groups, (d) K-POMS difference in waterfront with different groups, (e) K-POMS difference in green with different groups. (** means $P\text{-value} < 0.001$, * means $P\text{-value} < 0.05$)

Figure 4

Differences in the heart rate variability (HRV) between before and during VR stimuli experience different results. (a) HRV difference according to space function, (b) HRV difference in reference with different groups, (c) HRV difference in urban with different groups, (d) HRV difference in waterfront with different groups, (e) HRV difference in green with different groups. (** means $P\text{-value} < .001$)

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- [Data.xlsx](#)