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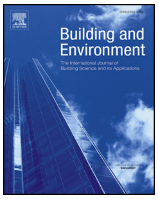

Effects of noise sensitivity on psychophysiological responses to building noise

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ABSTRACT

The present study aims to explore the effects of noise sensitivity on psychophysiological responses to floor impact noises and road traffic noise. A standard impact source (i.e. an impact ball) and two real impact sources (i.e. an adult's walking and a child's running) were used to record floor impact noises, while road traffic noise was introduced as an outdoor noise stimulus. A total of 34 subjects were recruited based on their self-rated noise sensitivity and classified into low and high noise sensitivity groups. During the laboratory experiments, all the noise stimuli were presented for 5 min each, and the subjects rated their annoyance with each stimulus at the end of each session. Their physiological responses (heart rate: HR, electrodermal activity: EDA, and respiratory rate: RR) were measured throughout the experiment. The obtained noise annoyance ratings increased with increasing noise levels for all the sources, and the high noise sensitivity group exhibited higher annoyance ratings than the low noise sensitivity group. All physiological measures varied significantly with the duration of noise exposure. In particular, the EDA and RR values decreased sharply after 30 s, demonstrating strong habituation over time. Noise sensitivity was found to significantly affect physiological responses, whereas noise levels showed no significant influence.

1. Introduction

It is well-known that both acoustic and non-acoustic factors contribute to noise annoyance [1–6]. In particular, noise sensitivity has been reported as a significant non-acoustic factor affecting annoyance. Several studies have concluded that subjectively reported noise sensitivity alters the effect of noise exposure on annoyance [7–9], while others have confirmed that annoyance ratings are greater for people with higher noise sensitivities [10,11]. Recent studies have also indicated that the prediction of noise annoyance can be considerably improved by adding noise sensitivity [12,13]. However, research to date has tended to focus on outdoor environmental noise (i.e. road traffic and aircraft noise), while little attention has been paid to indoor noise such as noise from neighbours.

Recent evidence has highlighted that annoyance is related to non-auditory effects of noise, such as physical and mental health problems [5,14–16]. Guski [5] suggested that a relationship exists between annoyance and negative feelings caused by noise, while Stansfeld and Matheson [14] reported that noise might have serious psychological effects. Furthermore, Maschke and Niemann [16] found that annoyance induced by neighbour noise had negative effects on both physical and mental health, such as cardiovascular health risks, migraine, or depression. More recently, a series of studies on building noise proposed the relationship between the annoyance caused by floor impact noise and health-related complaints [17,18]. So far, however, there has been little discussion on the relationship between annoyance and physiological responses. In particular, physiological measurements have been mainly used for emotional states [19–21] and physical health risks [22–25].

Physiological parameters are responsive to various emotional states including threat, frustration, anger, startle, and (un)pleasantness. Therefore, an experimental setting with various stimuli (e.g. acoustic modalities) is widely used to investigate affective responses through physiological measures [20]. Several attempts have also been made to explore physiological changes due to arousal-evoking stimuli [26]. For instance, it was found that heart rates decelerate, while electrodermal activity and respiration increase [20,27–29] after presentation of stimuli. It was also observed that subjective estimations, particularly arousal and pleasantness, were linked to physiological changes [30–33]. In addition, several studies tried to investigate the impacts of acoustic stimuli on physiological responses. Björk [34] found that electrodermal activity increased for the stimuli exceeding 70 dBA.

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Stansfeld [35] claimed that most physiological responses to noise habituated rapidly and suggested that noise sensitivity was related to higher electrodermal activity and heart rate, indicating physiological arousal to noise [35]. Hume and Ahtamad [33] reported that unpleasant acoustic stimuli caused larger falls in heart rate, while more pleasant sound stimuli resulted in bigger rises in respiratory rate. However, the acoustic stimuli used in the aforementioned studies are steady-state sounds and only lasted for short time periods ranging from 4 to 30 s; thus, the impacts of acoustic stimuli on physiological responses are still questionable for realistic situations with longer durations of noise exposure.

Stansfeld [35] provided an extensive review on relationships between noise sensitivity and various responses to environmental noise. It was suggested that, for noise sensitive individuals, greater awareness of external events contributes to the physiological responses or vice versa [35]. In particular, it was reported that high noise sensitivity is associated with higher level of physiological arousal, phobic, and defence/startle responses, as well as slower habituation to noise [35]. These mechanism between noise sensitivity and physiological responses has been empirically validated by studies on environmental noise [8,11,35,36]. Bigger changes in heart rates [8,35], higher skin conductance levels, and slower habituation [11,35] were observed from noise sensitive subjects while they were exposed to high noise levels. In addition, Heinonen-Guzejev et al. [36] found a significant increase in cardiovascular mortality from noise sensitive subjects. On the other hand, there is a lack of evidence explaining the link between noise sensitivity and physiological response in the research field on building noise. It has been found that noise sensitive individuals reported higher annoyance to various kinds of indoor noise [37] including floor impact noise [17,18]. Furthermore, noise sensitivity has been reported to increase health complaints either directly or indirectly [17,18]. While the association noise sensitivity and physiological responses to building noise was not explored in detail, it is worth examining the response evoked by building noise and compare the responses between different noise sensitivities.

The main purpose of this study is to develop an understanding of how noise sensitivity might affect perception of noise and physiological responses to noise. It was hypothesised that psychophysiological responses to noise might be different across subjective noise sensitivity and types of noise sources. Therefore, the subjects were recruited based on their self-rated noise sensitivity and classified into low and high noise sensitivity groups. Transient building noise transmitted from the neighbours was used as a major type of noise stimuli, and steady-state noise (road traffic noise) was added for comparison. Laboratory experiments were conducted by using 5 min long noise stimuli. Noise annoyance was evaluated after each stimulus presentation, and three physiological measures (heart rate, electrodermal activity, and respiratory rate) were monitored throughout the experiment.

2. Methods

2.1. Subjects

A simple online survey was conducted in order to examine subjects' experience and attitude to floor impact noise. A link of the survey was emailed to people who showed their interest in participating in the experiment. They were asked to answer several questions about their demographic characteristics, residential situation, previous experience of being exposed to floor impact noise, noise sensitivity, and attitude to the noise source. For the attitude to the source, six questions about the upstairs neighbours [18] including ‘I am happy with living downstairs of my upstairs neighbours’ were asked, and the replies were rated on a 5-point scale. Noise sensitivity was evaluated using the 21 questions developed by Weinstein [38].

This study aimed to recruit more than 26 participants since this number of participants are required to obtain 0.8 of statistical power in correlation analysis. A total of 34 Korean subjects were chosen based on their responses. They included 13 males and 21 females aged between 30 and 48 (mean = 38.8, std. deviation = 5.3). Half of them were in their 30s, and the other half in their 40s. The median noise sensitivity score of the subjects (median = 81.5) was computed and used to split the subjects into one group exhibiting ‘low noise sensitivity’ (median = 61 and std. deviation = 6.6) and another exhibiting ‘high noise sensitivity’ scores (median = 99 and std. deviation = 5.9). As listed in Table 1, either group contained 17 subjects. Thirteen subjects were either not married or married but had no children, and others reported that they had one or more children. It was found that 14 subjects showed positive attitude to their upstairs neighbours, whereas negative attitude was found for 20 subjects. Attitude score difference between the low and high noise sensitivity groups was not significant. The mean duration of residency in their current accommodation was three years; thus the subjects were also divided into two groups based on whether they lived in their current residence for less or more than three years. Eighteen subjects had lived in their current residence for less than three years, while the rest had lived in their residences for more than three years. It was found that 12 subjects had experience of making noise complaints regarding the noise from their upstairs neighbours.

Table 1
Demographic and attitudinal factors for the subjects ($N = 34$).

		Number	%
Gender	Male	13	38.2
	Female	21	61.8
Age	30s	17	50.0
	40s	17	50.0
Noise sensitivity	Low	17	50.0
	High	17	50.0
Child(ren) at home	Yes	21	61.8
	No	13	38.2
Attitude to upstairs neighbours	Positive	14	41.2
	Negative	20	58.8
Length of residency	Less than 3 years	18	52.9
	More than 3 years	16	47.1
Experience of making noise complaints	Yes	12	35.3
	No	22	64.7

2.2. Stimuli

In the present study, both transient and steady-state noises were used as noise stimuli. Floor impact noise, which represented the transient noise, consisted of real and standard impact noises induced by human footsteps (hereinafter ‘real’ or ‘R’) and a standard heavy-weight impact source (impact ball, hereinafter ‘ball’ or ‘B’). Road traffic noise (hereinafter ‘traffic’ or ‘T’) representing the steady-state noise was introduced for comparison with transient noises. Floor impact noises were recorded in a test building with a low background noise level (~25 dBA). The floor layer of the test building consisted of a 210 mm thick concrete slab, 30 mm thick resilient material, 40 mm thick lightweight concrete, and 40 mm thick mortar. The room where the recording was carried out was furnished with wooden flooring. An adult walking barefoot (70 kg) and a child running barefoot (24 kg) were chosen as the dominant real sources in residential buildings [39], while an impact ball [40] dropped from 1 m height was used as standard impact noise. All the floor impact noises were recorded binaurally using a head and torso simulator (Brüel & Kjær Type 4128C) positioned on a sofa in the receiving room downstairs. The road traffic noise was recorded near a motorway in the suburb of Liverpool. A microphone (Behringer ECM8000) connected to a digital recorder (ZOOM H4n) was positioned 2 m away from the motorway and 1.5 m above the ground. The motorway width was 11 m (35 feet), and the average vehicle speed was ~60 km/h (37 mph). The traffic flow was fluctuating due to a

Table 2
Noise levels of stimuli (dBA): A-weighted maximum sound pressure level (L_{AFmax}), A-weighted equivalent sound pressure level ($L_{Aeq,5min}$), A-weighted sound exposure level (L_{AE}), and percentile sound pressure levels (L_{10} and L_{90}).

Stimuli source	Label	L_{AFmax}	$L_{Aeq,5\ min}$	L_{AE}	L_{10}	L_{90}
Ball	B40	40.0	29.3	54.1	32.5	24.4
	B50	50.0	37.8	62.6	41.8	25.2
	B60	60.0	47.6	72.4	51.8	29.4
Real	R40	40.0	30.1	54.9	34.0	25.5
	R50	50.0	38.9	63.7	43.6	30.7
	R60	60.0	48.9	73.7	53.6	40.8
Traffic	T40	48.8	40.0	64.8	44.1	28.5
	T60	68.8	60.0	84.8	64.1	48.5

roundabout located around 160 m (0.1 miles) away.

Using the recordings, all the noise stimuli were edited to have the duration of 5 min. For the floor impact noise, only signals in the right channel were extracted from the binaural recordings in order to avoid any possible effects of spatial characteristics on perception [41]. The ball noises recorded at regular intervals between the impacts were edited to replicate the footstep noise. For the road traffic noise, spectral filtering was applied to simulate the outdoor-to-indoor noise attenuation using the condition of a closed window. Of different simulated closed windows [42], an attenuation with a median degree of isolation was adopted in this study similarly to a previous study [43]. In this condition, the attenuation increased from 12 dB for the 16 Hz and 31.5 Hz octave bands up to 35 dB for the 8 kHz octave band [42,43]. Temporal features of the noise stimuli are listed in Table 2 in terms of A-weighted equivalent sound pressure levels (L_{Aeq}), A-weighted maximum sound pressure levels (L_{AFmax}), A-weighted sound exposure levels (L_{AE}), and the level exceeded for 10% of the measurement period (L_{10}). Fig. 1 shows the frequency characteristics of the two floor impact noises at 60 dBA (L_{AFmax}) and the road traffic noise at 60 dBA ($L_{Aeq,5\ min}$). Compared to the road traffic noise, the two floor impact noises show their dominant sound pressure levels at low frequencies below 125 Hz.

2.3. Experimental design

In the present study, all the noise stimuli lasted for 5 min to understand the variations of the physiological responses over time. It was also hypothesised that the noise level and type of impact source might affect the responses. The sound pressure levels of the floor impact noises (L_{AFmax}) were fixed at 40, 50, and 60 dBA because the floor impact noise was rarely noticed at levels below 40 dBA [17]. For comparison with the outdoor noise, the road traffic noises were set at 40 and 60 dBA (L_{Aeq}).

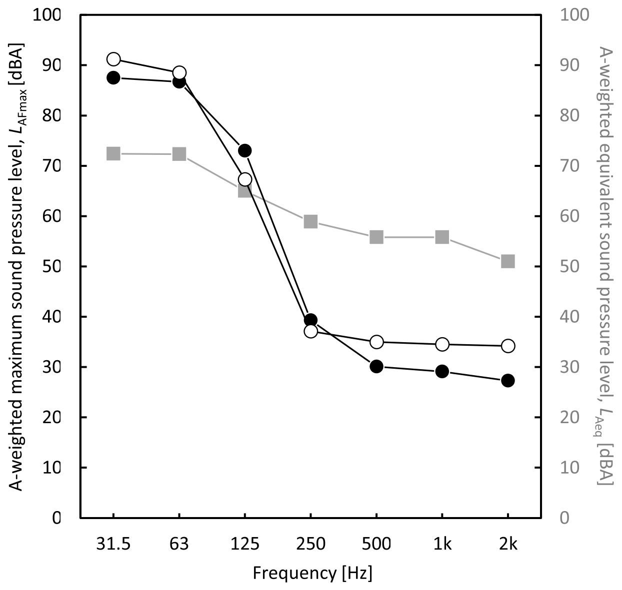

Fig. 1. Frequency characteristics of the noise stimuli. Black lines represent L_{AFmax} and grey line represents L_{Aeq}. ●: impact ball, ○: real impact source, and ■: road traffic.

Each subject took part in eight sessions with different noise levels and sources. The duration of each session was around 8 min including a rest period (i.e. baseline, 2 min), noise exposure (5 min), and evaluation of the noise annoyance (30s). All sessions were spaced at equal intervals of 2 min silent baselines and presented randomly in order to avoid any possible order effect [44].

The sounds above 63 Hz were reproduced using a loudspeaker (Genelec 8050 A), while the low-frequency sounds below 63 Hz were presented using a subwoofer (Velodyne MicroVee) placed in front of the subjects. A low-pass filter with a cut-off frequency of 63 Hz in the octave band was applied to the sounds reproduced by the subwoofer. An additional loudspeaker was used for producing ambient noise at 31 dBA.

2.4. Psychophysiological measurements

After the noise exposure for 5 min, the subjects were asked to rate their annoyance using an 11-point scale (0 = '*Not at all*' to 10 = '*Extremely*') at the end of each session. Three physiological responses were measured for the entire duration of each session: heart rate (hereinafter HR), electrodermal activity (hereinafter EDA), and respiratory rate (hereinafter RR). All physiological responses were recorded via a data acquisition system (BIOPAC Systems MP150) and analysed using AcqKnowledge 4.4 (BIOPAC Systems). Two wireless amplifiers were placed just outside the audiometric booth where the subject was seated in. The amplifiers received all the measurement data via Bluetooth transmitting mode. The HR was derived from raw electrocardiograph data which were measured using three electrodes attached to the subject's right wrist and both ankles. The EDA was measured using two electrodes attached to the subject's index and middle fingers of the right hand. The RR was computed from raw respiration data which were measured through a respiration transducer belt worn around the subject's chest.

2.5. Procedure

The subjects were asked to avoid staying up late and drinking alcohol the night before the experiment and to avoid drinking any caffeinated drinks on the day of the experiment. The experiment was carried out in an audiometric booth where the background noise level was approximately 25 dBA. All the electrodes were attached to the subject's body once the subject finished reading the information sheet regarding the experiment and gave their consent to participate. The subject was then helped to be seated comfortably on a chair. Road traffic noise was played over a loudspeaker positioned 2 m in front of the subject, while floor impact noise was played over another loudspeaker positioned above the subject. Each subject took part in a test session at the beginning which lasted from three to 5 min in order to get all the measurement systems checked and calibrated before the experimental sessions. The room temperature and humidity were kept constant throughout the experiment to avoid their effects on the physiological responses [29].

2.6. Data analysis

Any erroneous data were discarded before the analysis [33,44], and the identified respiratory irregularities were used for judging and removing the remnant artifacts in the EDA and HR [45]. Due to the variations of the subjects' physiological responses, percentage changes

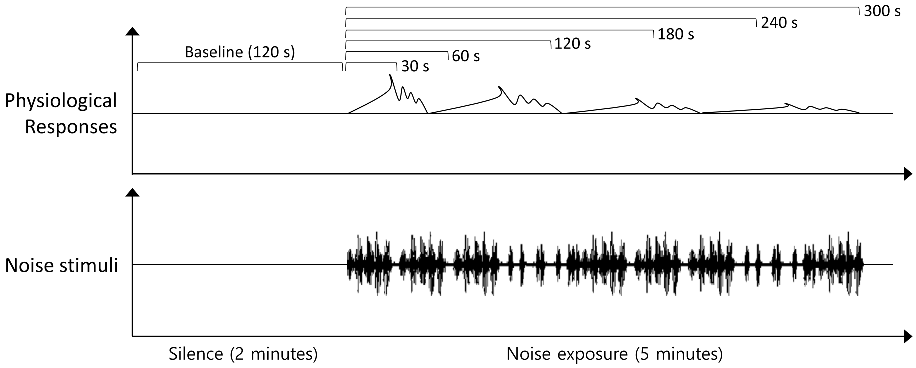

Fig. 2. Calculations of physiological responses for different durations of noise exposure (30 s, 1 min, 2 min, 3 min, 4 min, and 5 min).

(%) representing the physiological response changes from the baseline to noise exposure were calculated [46]. All the psychophysiological responses were additionally analysed to find out whether they were influenced by acoustic or non-acoustic factors. Thus, the effects of different noise levels, noise sources, noise sensitivities, and the duration of noise exposure on the psychophysiological responses were investigated. In particular, six time blocks of physiological data were analysed in order to examine whether the physiological responses varied over the 5 min intervals. Fig. 2 shows a simple illustration how all the physiological responses were computed for 30 s, 1 min, 2 min, 3 min, 4 min, and 5 min from the beginning of the noise exposure. Mean percentage changes for these six durations were calculated and compared with the mean percentage changes for the baseline before each noise exposure. As potential factors affecting the responses, several demographic factors were also considered: age, gender, duration of residency, and number of children living in the current residence. Impacts on the responses of the attitude to the noise source (upstairs neighbours) and past experience of making noise complaints were also examined.

Statistical analyses were performed using SPSS for Windows (version 22.0, SPSS Inc., Chicago, IL). Main effects of noise levels, type of sources, and duration of exposure on annoyance and physiological responses were assessed using a repeated measures analysis of variance (ANOVA). Wilcoxon signed ranks test was used to compare two related samples such as annoyance ratings of Ball and Real, while Mann-Whitney *U* test was used to test all responses between groups (e.g. noise sensitivity). In addition, an independent samples *t*-test was used to compare independent groups (e.g. the low and high noise sensitivity groups). In the present study, *p* values of less than 5% ($p < 0.05$) were considered as statistically significant.

3. Results

3.1. Noise annoyance

Fig. 3 shows the mean annoyance ratings for different noise stimuli as functions of L_{AFmax} and L_{AE}. It was found that the noise annoyance ratings increased with increasing noise level for all noise sources. The results of the repeated measures ANOVA confirm that the effect of the noise level on annoyance was significant [$F(1, 40) = 77.20, p < 0.01$]. The correlation coefficients between the annoyance ratings and noise level were 0.78 and 0.75 for the ball and the real, respectively ($p < 0.01$ for all). It was observed that the main effect of the impact noise type (ball or real) on annoyance is also significant [$F(1, 33) = 20.18, p < 0.01$]. It was found that the annoyance ratings for the real were significantly higher than the ratings for the ball at 40 and 60 dBA, which will be denoted as B40 and B60 in the following for the sake of convenience. This might be because the L_{AE} levels are quite different even at the same L_{AFmax} levels. For example, the difference in L_{AE} between the noises was 1.3 dB at $L_{\mathrm{AFmax}} = 60$ dBA. The annoyance rating for the T40 case was close to those for B50 and R50 because the corresponding noise levels are similar in terms of L_{AFmax} and L_{AE}. It was also found that the annoyance rating for T60 was significantly greater than those for other stimuli.

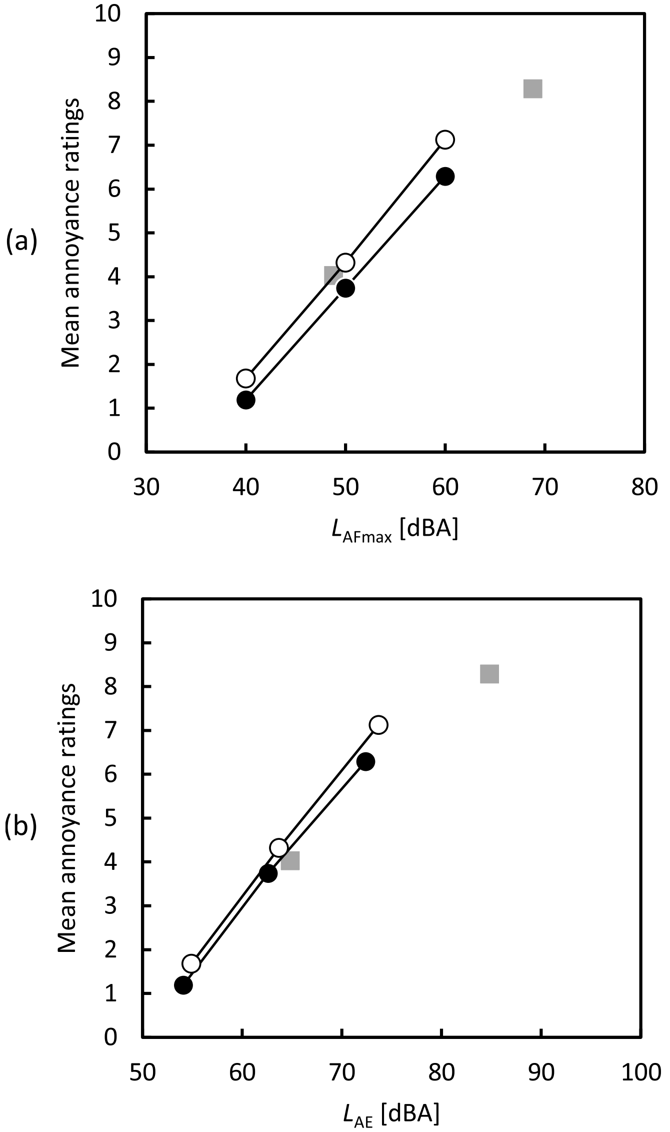

Fig. 3. Mean annoyance ratings as functions of (a) L_{AFmax} and (b) L_{AE}. ●: impact ball, ○: real impact source, and ■: road traffic.

In order to investigate the effect of noise sensitivity on noise annoyance, the noise annoyance ratings from the groups with low and

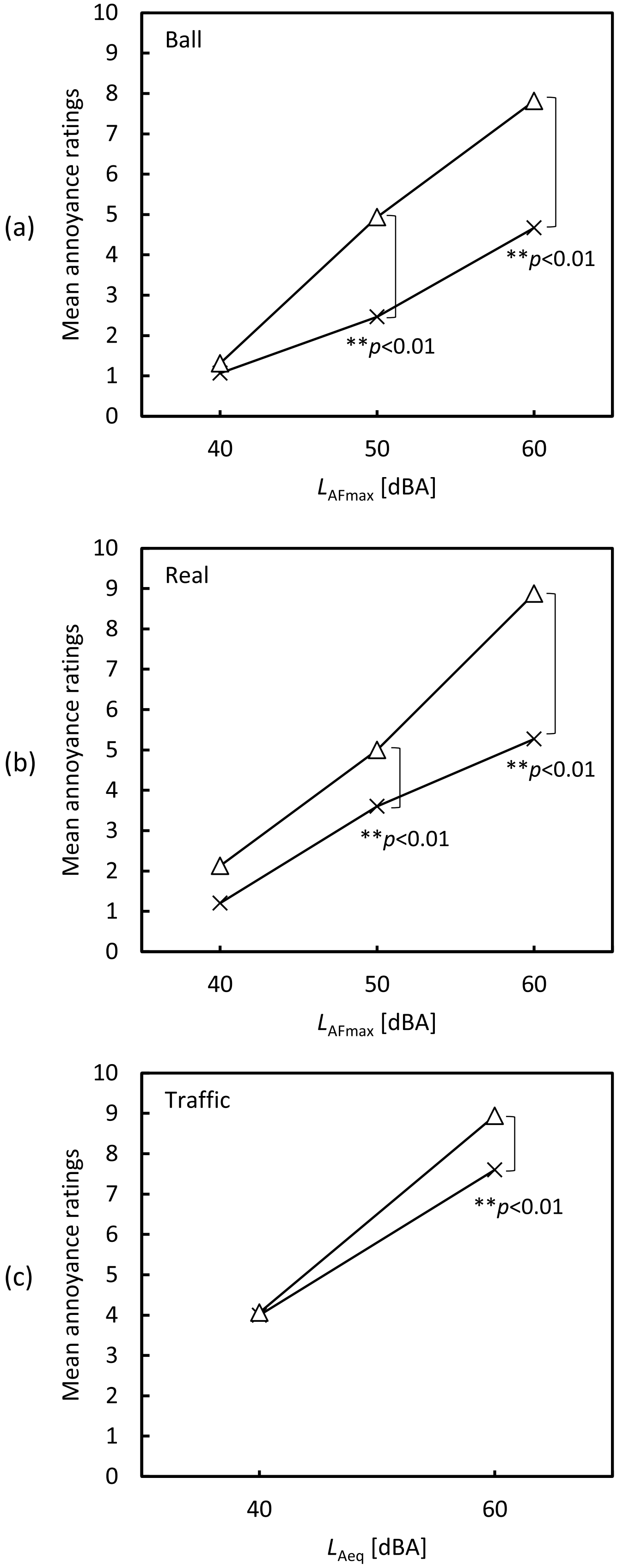

Fig. 4. Mean annoyance ratings for the low and high noise sensitivity groups: (a) impact ball, (b) real impact source, and (c) road traffic. Asterisk indicates significant differences between the low and high noise sensitivity groups ($p < 0.01$). ×: low noise sensitivity group and △: high noise sensitivity group.

high noise sensitivity scores were compared. As shown in Fig. 4(a) and Fig. 4(b), for the floor impact noise, the high noise sensitivity group reported greater annoyance ratings than the low noise sensitivity group. The differences between the two groups increased with increasing noise levels, and significant differences were found at 50 and 60 dBA. A similar tendency was found for the road traffic noise, with a significant difference between the groups at 60 dBA. For the low noise sensitivity group, the noise level showed a significant impact on annoyance [$F(1, 21) = 19.40$, $p < 0.01$], while the impact noise type (ball or real) also had a main effect on annoyance [$F(1, 16) = 11.51$, $p < 0.01$]. The correlations between the annoyance ratings and noise level were statistically significant ($r = 0.73$, $p < 0.01$ for the ball and $r = 0.71$, $p < 0.01$ for the real). Similarly, for the high noise sensitivity group, the main effect of the noise level on annoyance [$F(1, 22) = 165.31$, $p < 0.01$] and the influence of the impact noise type on annoyance [$F(1, 16) = 8.34$, $p < 0.05$] were statistically significant. The relationships between the annoyance ratings and noise level were also significant, and the correlation coefficients were greater than those for the low noise sensitivity group ($r = 0.93$, $p < 0.01$ for the ball and $r = 0.88$, $p < 0.01$ for the real). Result of Fisher's exact test confirmed that the correlation coefficients of the low and high noise sensitivity groups were significantly different ($p < 0.01$).

3.2. Physiological responses

In order to investigate how the physiological responses changed over time, the mean changes of the HR, EDA, and RR were calculated for different durations of noise exposure ranging from 30 s to 5 min. As shown in Fig. 5, the mean changes of the HR slightly increased for longer durations for both low and high noise sensitivity groups. Compared to the HR, the EDA and RR showed more pronounced dependencies on the noise exposure duration, initially increasing and then rapidly decreasing as the duration increased. For instance, for the road traffic noise, the low noise sensitivity group showed large variation of the mean change of EDA from around 2% to −5%. As listed in Table 3, the results of the repeated ANOVA confirm that the mean changes of the HR, EDA, and RR were significantly affected by the duration of noise exposure ($p < 0.01$ for all the measures and sources). Fig. 5 compares the differences between the two noise sensitivity groups. Both groups showed similar tendencies over time; however, the changes of the high noise sensitivity group were greater than those of the low noise sensitivity group. In particular, the RR showed a significant difference between the groups for all the noise sources. For the low noise sensitivity group, the mean changes of the RR recovered and showed negative values after 5 min, whereas those of the high noise sensitivity group still remained positive, implying that 5 min might not be sufficient for sensitive people to fully recover.

It is of note that the decrease of the mean changes of the EDR and RR was most significant between 30 and 60 s. This implies that the initial changes of the physiological responses (e.g. the HR deceleration, EDA increase, and RR acceleration observed for 30 s) represent arousal status [26], and the physiological responses start to recover after 30 s. Previously, Park and Lee [47] also found that arousal was caused by 23 s long stimuli of floor impact noise. Therefore, in the present study, only the mean changes for 30 s were used for the detailed analysis.

The changes in the HR, EDA, and RR for 30 s were averaged across the noise sources and are plotted in Fig. 6. The mean changes are also listed in Table 4 together with standard deviations. The HR decreased after the noise exposure, whereas the EDA and RR increased for both low and high noise sensitivity groups. The differences between the baseline and the noise exposure were statistically significant for all the noise sources and all the physiological measures ($p < 0.01$ for all). For the impact ball, the HR of the low noise sensitivity group decreased to −1%, whereas that of the high noise sensitivity group dropped to around −3% on average. Similarly, after the presentation of real impact sources and road traffic noise, the high noise sensitivity group

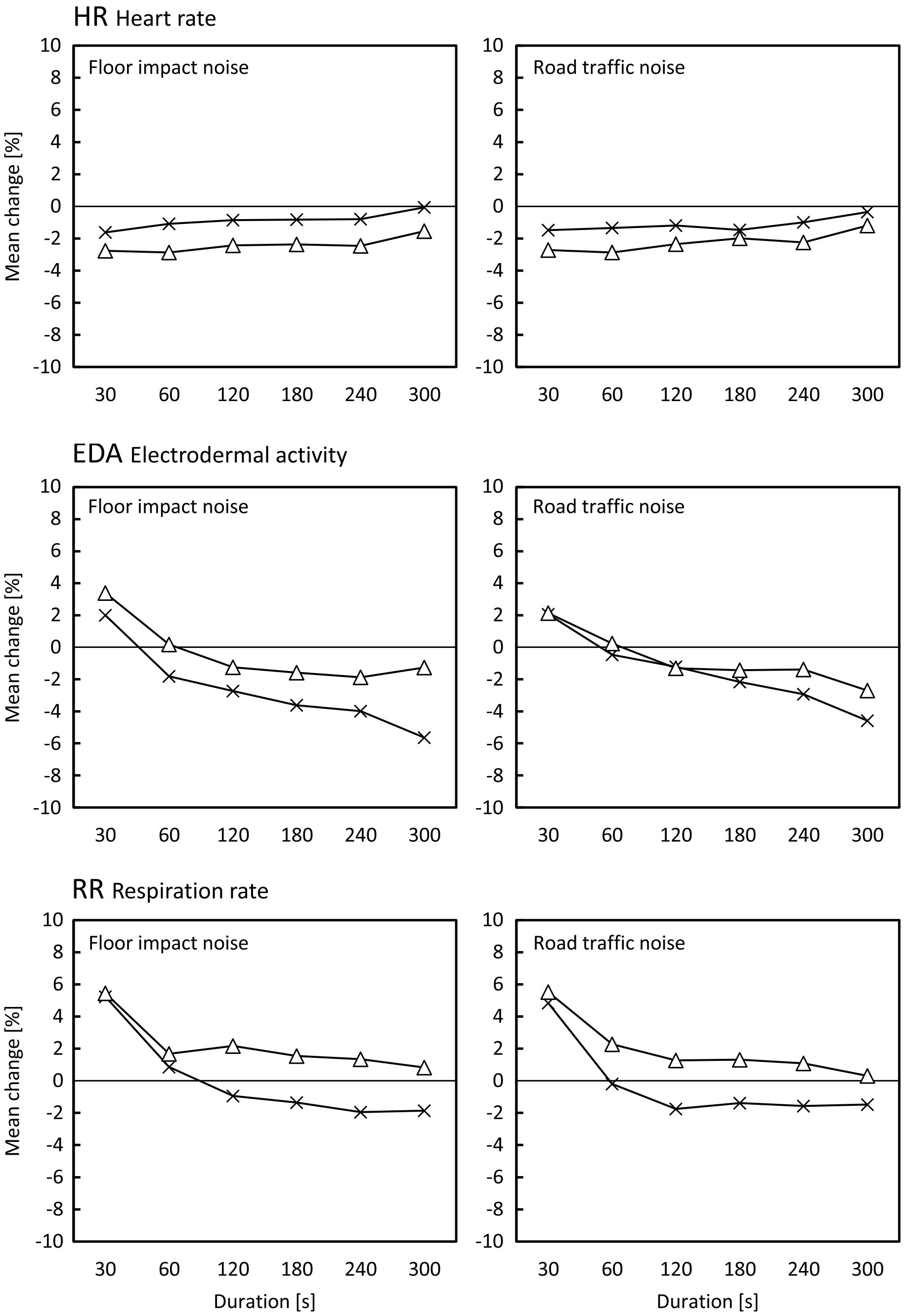

Fig. 5. Mean changes of physiological responses over different durations of noise exposure for the low and high noise sensitivity groups. ×: low noise sensitivity group and △: high noise sensitivity group.

Table 3
Results of the repeated measures analysis of variance (ANOVA) showing the effect of the varying duration of noise exposure on the HR, EDA, and RR (*$p < 0.01$).

		Impact ball		Real impact source		Road traffic	
		df	F	df	F	df	F
HR	Duration	4	9.43*	4	17.49*	4	12.26*
(Heart rate)	error	130		127		126	
EDA	Duration	2	26.91*	2	20.74*	3	22.08*
(Electrodermal activity)	error	80		61		99	
RR	Duration	3	29.06*	3	26.49*	3	22.46*
(Respiration rate)	error	99		93		91	

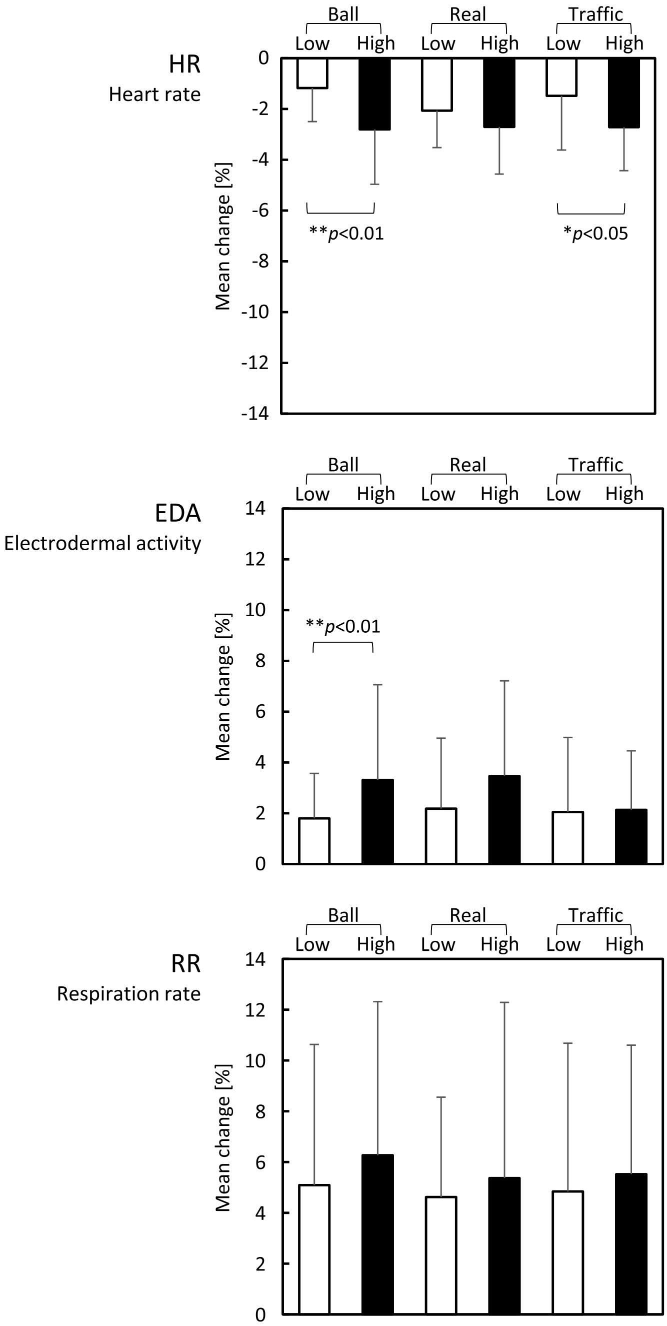

Fig. 6. Mean changes of physiological responses for the low and high noise sensitivity groups with error bars indicating standard deviations. Single and double asterisk indicates significant differences between the low and high noise sensitivity groups.

showed greater changes in the HR than the low noise sensitivity group. The independent samples *t*-test confirmed that the differences in the HR between the two groups were significant for the impact ball and road traffic noise ($p < 0.01$ for both). For the EDA, the high noise sensitivity group showed greater changes than the low noise sensitivity group for all the sources, although the difference between the groups was significant only for the impact ball ($p < 0.01$). The impact ball raised the EDA of the low noise sensitivity group by 1.80%, while the mean change of the high noise sensitivity group was more than 3% on average. For the RR, the mean changes of the high noise sensitivity group were slightly greater than those of the low noise sensitivity group; however, the differences between the groups were not significant.

The mean changes of the HR, EDA, and RR for different noise levels are plotted in Fig. 7 for the two noise sensitivity groups. The results of the repeated measures ANOVA confirmed that none of the physiological responses were significantly influenced by different noise levels and different impact sources. The decrease in the HR of the high noise sensitivity group was greater than that of the low noise sensitivity group at all levels and for all noise sources; however, there seemed to be no significant relationship between the HR changes and noise levels. The statistical significance of the differences between the two noise sensitivity groups was found at B50, B60, and R50. It was observed that the high noise sensitivity group showed greater EDA than the low noise sensitivity group at all noise levels and for both impact noise sources. However, there was no significant difference in the EDA between the two noise sensitivity groups. The RR showed no clear tendency with increasing noise level, and a significant difference between the two noise sensitivity groups was found only at B40.

4. Discussion

4.1. Impacts of noise sensitivity on annoyance and physiological responses

The majority of previous studies have mainly focused on the effects of noise sensitivity on annoyance ratings for outdoor noises such as environmental noise [3,8–11]. In contrast, the present study examined indoor building noise (i.e. floor impact noise), as well as outdoor noise (i.e. road traffic noise). The findings from the laboratory experiment revealed that high noise sensitivity significantly increased noise annoyance ratings of the indoor and outdoor noises. These results are consistent with the findings of previous studies [4,7,8,10,11,17,48,49], where noise sensitivity was found to be a crucial factor affecting annoyance for the case of environmental noises. Furthermore, the findings of this study confirm that noise sensitivity influences annoyance for indoor noise by extending an earlier study [37] on the impacts of noise sensitivity on annoyance ratings for airborne and bathroom drainage noises.

Confirming findings in a recent laboratory experiment [47], this study found decelerations in HR, increases in EDA, and accelerations in RR at the beginning of the noise exposure. Decelerating HR and increasing EDA indicate that the subjects were in 'freezing' stage accompanying with focused attention and potentiated startle [26]. In

Table 4
Mean and standard deviation values of the HR, EDA, and RR for different noise sources and noise sensitivity groups.

	Noise sensitivity group	Impact ball		Real impact source		Road traffic	
		Mean [%]	Std. Deviation	Mean [%]	Std. Deviation	Mean [%]	Std. Deviation
HR	Low	−1.18	0.01	−2.07	0.01	−1.48	0.02
(Heart rate)	High	−2.81	0.02	−2.71	0.02	−2.72	0.02
EDA	Low	1.80	0.02	2.19	0.03	2.05	0.03
(Electrodermal activity)	High	3.31	0.04	3.46	0.04	2.14	0.02
RR	Low	5.09	0.06	4.62	0.04	4.84	0.06
(Respiration rate)	High	6.27	0.06	5.37	0.07	5.52	0.05

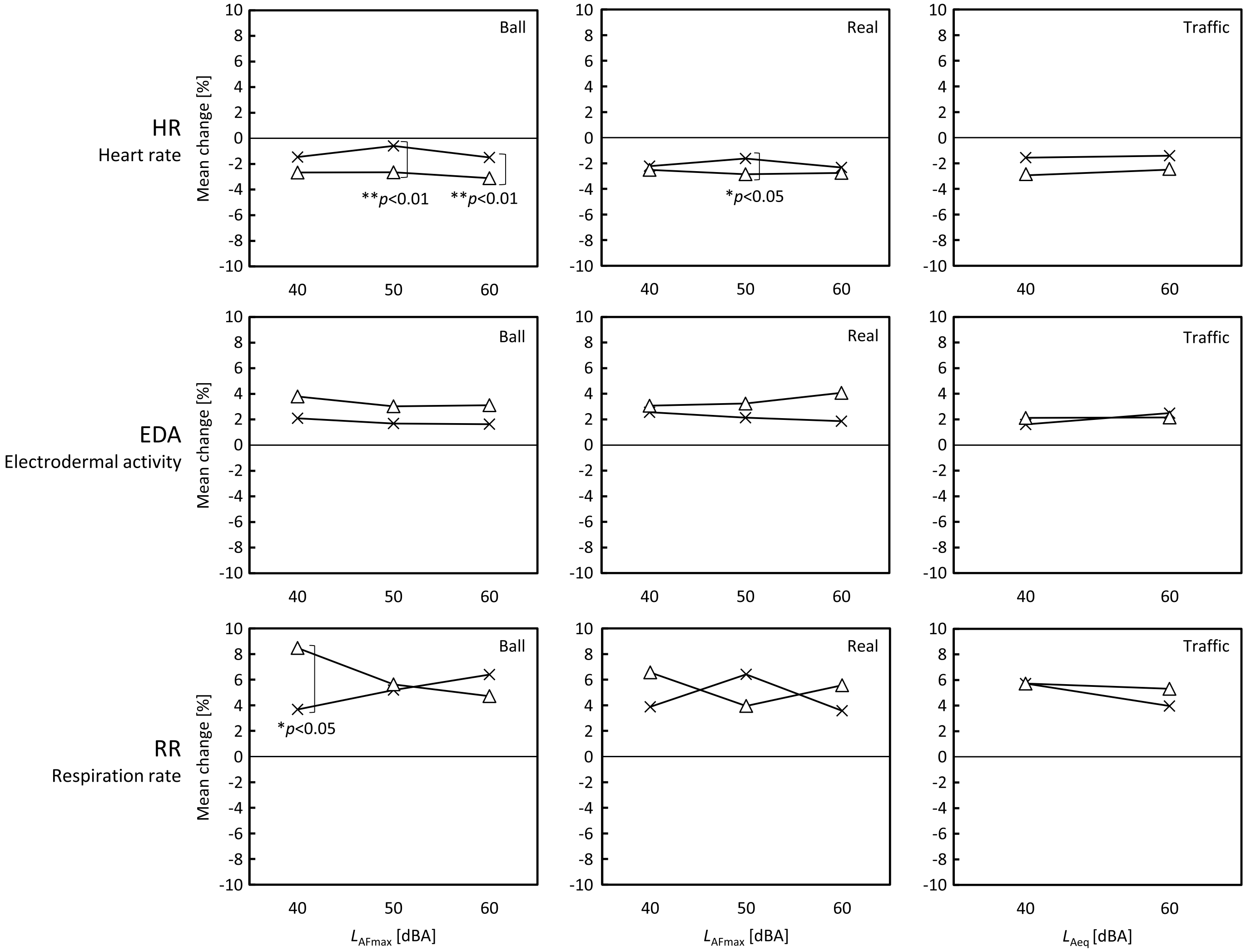

Fig. 7. Mean changes of physiological responses along with noise levels for the low and high noise sensitivity groups. Single and double asterisks indicate significant differences between the low and high noise sensitivity groups. ×: low noise sensitivity group and △: high noise sensitivity group.

other words, the exposure to the noise stimuli evoked ‘freezing’ responses from the participants. In contrast, HR accelerates and EDA keeps increasing in the ‘circa-strike’ stage where individuals take either ‘fight or flight’ response [26]. This study also showed that physiological responses to noise were significantly different for varying noise sensitivity. In particular, the changes in physiological responses from noise sensitive group were greater than those from the low noise sensitivity group. Greater deceleration in HR and greater increases in EDA and RR were found from the subjects with high noise sensitivity for all the noise sources, durations, and most of the noise levels. These results imply that the subjects with higher noise sensitivity had the greater 'freezing' responses because they paid more attention to the stimuli compared with subjects with low noise sensitivity.

In previous studies, noise-sensitive subjects showed higher EDA and HR [35] and cardiovascular mortality significantly increased among noise-sensitive women [36]. This study also found different physiological responses between low and high noise sensitivity groups. However, the findings of this study showed a partial disagreement with Stansfeld [35] because, in the present study, noise sensitive subjects consistently showed lower HR compared to subjects with low noise sensitivity. This disagreement can be explained by different noise levels at which the noise stimuli were presented. In the present study, noise levels varied between 40 and 60 dBA, whereas Stansfeld [35] presented the stimuli in the region between 75 and 100 dBA. This implies that noise sensitive subjects in this study paid more attention to the stimuli than low noise sensitivity group in the ‘freezing’ stage [26], whereas noise sensitive subjects in the previous study [35] were in the ‘circa-strike’ stage due to greater noise levels, representing bigger ‘alarmed’ response than low noise sensitivity group.

4.2. Other factors affecting noise annoyance and physiological responses

The findings of the present study are in agreement with previous studies [50–52] reporting that noise annoyance is significantly affected by sound pressure levels. In particular, this result is in good agreement with the work of Park and Lee [47], where the annoyance caused by floor impact noise increased with the noise level. Contrary to the noise annoyance, physiological responses were not affected by the noise levels for different noise sources. However, Park and Lee [47] recently reported that the EDA and RR changes were correlated with sound pressure levels for floor impact noises. The disagreement may be attributed to the different settings of the laboratory experiments. Park and Lee [47] employed a wider range of sound pressure levels (from 31.5 to 63 dBA, L_{AFmax}) than the current study; thus it was possible to investigate the relationship between the noise levels and physiological responses. In comparison, in the present study we carried out tests only for three sound pressure levels with longer noise exposure and focused on the effect of noise sensitivity, so the limited data did not allow us to confirm the impact of the noise levels on the physiological responses.

Park and Lee [47] previously reported that annoyance ratings and physiological responses showed significant differences for different types of impact sources (ball or real). However, the present study did not find such differences in the physiological measures, which might be due to the differences in the time histories of the impact ball noises used here. In the previous study [47], the impact ball noises consisted of ten single impulsive noises at regular intervals and showed significantly different waveforms compared to the real noises. In contrast, the present study edited the impact ball noises to replicate the waveforms of the real impact noises. This result implies that human hearing and perception (i.e. subjective annoyance rating) are more sensitive than physiological responses to the differences between the impact ball and real impact noises.

In the present study, it was found that none of the demographic factors such as age and gender affected the annoyance ratings and physiological responses. Several studies [48,49,53] have reported that attitudinal factors affected noise annoyance; however, this was not the case in the present study. This indicates that the questions used in this study to measure the attitude of the subjects to the noise source might have not been chosen in the best way. In contrast to the environmental noise studies [49,53,54], where the noise sources are clear and simple, it is much more complicated to identify the sources in apartment buildings. Therefore, in the present study, the attitude to the noise from the upstairs neighbours was assessed assuming that this type of noise sources would be dominant. Nevertheless, the findings of this study suggest that direct questions about the subject's attitude to noise or their emotions expressed under noise exposure might be useful in the future.

4.3. *Effects of noise exposure duration on annoyance and physiological responses*

The laboratory experiment showed significant effects of noise exposure duration on all the physiological responses, with the HR accelerating and EDA and RR decreasing for longer durations. The acceleration of the HR can be interpreted by the subjects experiencing stronger arousal based on the model stating the relationship between physiological responses and arousal intensity [26]. According to the model proposed by Lang et al. [26], the HR accelerates with increasing arousal intensity. However, an increase in the HR can also be seen even as the habituation to the stimuli or recovery phase occur after a certain degree of deceleration [55]. Habituation is defined as a decrease in the strength of the response after repeated presentation of the same stimulus [56]. During the laboratory experiments, the noises induced by footsteps and vehicles were repeated for 5 min; thus, the responses evoked by the same stimulus could decrease. Similar tendencies were found in the EDA and RR changes, indicating strong habituation over time [55,57]. The EDA and RR increased by the initial stimulus presentations and then sharply decreased after 30 s. Most changes in the EDA and RR over time stabilised in the region between 1 min and 5 min. These results clearly indicate that the subjects experienced arousal in the very beginning due to the noise stimuli, but their responses started to habituate after a certain period of time. Previous studies [58,59] have also reported that the initial arousal responses changed and recovered over time. Brosschot and Thayer [58] measured the HR together with the emotional arousal eight times for each participant, at 1-h intervals. They reported that negative emotions delayed HR recovery compared to positive emotions [58]. In addition, Gerin et al. [59] carried out HR and blood pressure measurements simultaneously with performing anger-recall tasks. They found longer blood pressure recovery time from participants who tended to ruminate about their past events which provoked anger [59]. As both previous studies [58,59] suggested, it can be assumed that emotional responses have meaningful impacts on physiological responses. Future research on emotional responses evoked by floor impact noise would be of worth assessing in order to understand broader responses to this noise issue.

5. Conclusion

The present study investigated psychophysiological responses (annoyance, HR, EDA, and RR) to floor impact noises and road traffic noise for the low and high noise sensitivity subject groups. It was found that the annoyance ratings increased with increasing sound pressure levels (40, 50, and 60 dBA for the floor impact noises (L_{AFmax}) and 40 and 60 dBA for the road traffic noise (L_{Aeq})). The high noise sensitivity group showed significantly greater annoyance ratings than the low noise sensitivity group for all the sources. The physiological responses to noise stimuli were calculated for different durations of noise exposure from 30 s to 5 min. The EDA and RR initially increased and then rapidly decreased after 30 s, indicating strong habituation over time. Deceleration of the HR and increase of the EDA and RR were found during 30 s noise exposure; the high noise sensitivity group showed more pronounced changes in the physiological responses than the low noise sensitivity group. The physiological responses were not affected by the type of noise source (standard or real impact source) and the sound pressure level. Age, gender, and attitude to the noise source did not affect the annoyance ratings and physiological responses. The findings of this study could contribute to the development of guideline and policy on building noise by considering the residents' subjective noise sensitivity. Further study is needed to confirm the variations in the physiological responses due to noise exposure in real situations.

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