Emotions and physiological responses elicited by neighbours sounds in wooden residential buildings

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Abstract

This research set out to investigate emotions and physiological responses elicited by neighbour sounds in wooden residential buildings. A laboratory experiment was performed in an audiometric booth with individual (i.e. footsteps, speech, or music) and combined sounds (i.e. footsteps in combination with music or speech) from neighbours. Participants performed a self-assessment of their levels of arousal and valence using the Self-Assessment Manikin (SAM). The participant's physiological responses were also monitored throughout the experiment in terms of facial electromyography (fEMG in the corrugator supercilii (CS) and zygomaticus major (ZM) muscle groups), heart rate (HR) and electrodermal activity (EDA). The results showed that arousal and valence ratings of individual and combined sounds were organised along the defensive motivation circuit. The impact of sound pressure level (SPL) on affective ratings were significant except for individual music clip and footsteps sound combined with music. Listening to neighbour sounds evoked significant activities in physiological responses. Compared with the baseline only with ambient noise, neighbour sounds evoking affective responses led to an increase in fEMG CS activity and to a decreases in fEMG ZM activity, HR and EDA. The differences in fEMG ZM activities between individual and combined sounds were significant and the SPL had little effect on physiological responses. Arousal ratings were significantly correlated with fEMG CS activity, while valence ratings were strongly associated with EDA. The affective ratings were influenced by self-rated noise sensitivity, but this was not the case for physiological responses.

1. Introduction

Emotions are central in the life regulating processes of living creatures, playing a key role in individuals' psychological and physical health [1-5]. Emotional competent stimuli causing chemical and neural responses surround us every day and may involve all our senses. In particular, the auditory channel is one of the most powerful means of inducing and communicating emotions in people [6]. For example, environments without acoustic stressors may induce positive emotions and motivate an approach response (the so-called appetitive motivation system), while places with auditory stressors tend to induce negative emotions and motivate an avoidance response (i.e. the defensive motivation system). Similarly, positive soundscapes promote psycho-physiological restoration [7], whereas disagreeable soundscapes might negatively affect people's well-being and long-term health [8-10]. Some studies have examined the emotional responses to acoustic stimuli to understand the subjective nature of the effects of noise [11]. Asutay et al. [12] investigated how auditory stimuli can induce emotional reactions and how these are influenced by the subjective meanings as well as the physical properties of the sounds. Tajadura-Jiménez et al. [13] also reported that unpleasant sounds evoked more intense emotional responses than emotionally neutral or pleasant sounds. Furthermore, Fields [14] found that more fearful sounds were more annoying and Stansfeld et al. [11] suggested that noise that impairs a person's wellbeing would be more prejudicial to health than noise that causes only mild irritation.

Affective reactions to stimuli such as sonic events have been measured in terms of valence and arousal [13, 15-17]. Valence is a basic dimension of all affective responses and may account for between 50% and 60% of the variance in emotional responses [18]. Arousal is a second orthogonal dimension of experience that relates to how arousing or active versus passive the experience is and often accounts for half as much variance if compared to valence. The valence–arousal model is inherently associated with the process of cognitive evaluations of stimuli, and thus with physiological responses [19]. Accordingly, many studies have measured affective ratings coupled with physiological responses to stimuli, such as facial electromyography (fEMG) for recording stomatic responses and heart rate (HR) and electrodermal activity (EDA) for measuring visceral changes [20-23]. Acoustic research has also frequently measured facial reactions to investigate emotional states emerging during exposure to auditory stimuli [24, 25]. In particular, positive acoustic stimuli evoked an increase in the zygomaticus major muscle group activity (e.g., smiling), whereas negative sounds spontaneously increased the corrugator supercilii muscle group activity (e.g., frowning) [25, 26]. The HR responses to sound stimuli were also used to differentiate conscious and unconscious emotional experiences elicited by everyday and archetypal sounds [27]. Previous studies have reported decelerations in HR during exposure to negative sounds such as floor impact sound and traffic noise [16, 17, 19, 28, 29]. Similarly, EDA provided a reliable quantification of autonomic expressions of emotions in the auditory domain [30] and significantly changed after listening to emotionally evocative sounds [31] and concert hall music [32].

Some researchers have combined the assessment of affective ratings with the measurement of several physiological responses to sounds at once. Bradley and Lang [17] reported that listening to unpleasant everyday sounds resulted in larger fEMG activity in the corrugator supercilii muscle group and larger HR deceleration when compared to pleasant ones. The authors also found that EDA elicited by emotionally arousing sounds was larger than the EDA in response to neutral sounds. Medvedev et al. [19] examined emotional response with HR and EDA after the presentation of natural and urban sounds and found that the least pleasant sounds showed larger changes in EDA and smaller changes in HR change than more pleasant sounds. A similar study that utilised emotion (i.e. pleasantness and arousal) and physiological response (i.e. HR, and fEMG) [28] found that unpleasant soundscape recordings led to a decrease in HR and an increase in fEMG activity in the corrugator muscle group. Similarly, Gomez and Danuser [16] highlighted significant relationships between arousal ratings and HR for environment noise and between arousal ratings and EDA for music. Moreover, a similar approach was taken by Irwin et al. [33], who found that HR was not significantly altered by the pleasantness of urban soundscape recordings. However, the reports of a link between affective ratings and physiological responses to acoustic stimuli are still not consistent; thus, more research is required to understand people’s reactions to everyday sounds [34].

Even though the majority of discussion on emotions evoked by acoustics events dealt with outdoor soundscape, indoor soundscape research has recently started to examine how people’s health and well-being can be enhanced by the built environment [35-37]. For example, Dokmeci et al [38, 39] investigated indoor soundscapes in libraries using a newly developed questionnaire which deals with baseline characteristics of listeners and their interference with the acoustic and spatial environments. They included noise from neighbouring spaces as a factor affecting listeners’ expectations. In addition, indoor sounds at home have been reported as a common cause of annoyance and affect various emotional and visceral responses, stress and mental health [11, 35-37, 40-42]. Furthermore, the chance of reporting annoyance at home increased compared with other everyday scenarios (e.g., work and leisure) [43]. Hence, some investigations have focused on the acoustics of indoor residential spaces. Grimwood [44] found that people experienced various negative emotional statuses, such as stress, embarrassment, worry, irritation, and depression, from poor sound insulation at home. Moreover, a national noise attitude survey in the UK [45] reported two relatively discrete types of emotional response to noise: 1) more outwardly-directed aggression characterised by feelings of annoyance, aggravation, bitterness and anger toward the source and 2) more inward reaction, evoking such emotions as tension, anxiety, and pressure. Jo et al. [46] also classified 54 different impact sounds from upstairs neighbours using semantic expressions. They reported that the downstairs residents’ annoyance was related to the categories of Dissatisfaction, Irregularity, and Discontinuity. Torresin et al. [47] proposed a principal components model of acoustic perception in residential buildings, consisting of comfort, content and familiarity. Aletta et al. [37] also investigated soundscape quality in the living room of Belgian nursing homes insisting further attention on the potential role of the acoustic environment and proposing active soundscape approaches (e.g., using the residents’ sensitivity and preference for specific sounds). Kerr et al. [41] explored the emotional experiences of living and parenting in high-rise apartments in newly densifying cities and argued that sound is a key locus of contestation shaping families' emotional geographies. Similarly, Park et al. [42] investigated emotion lexicons evoked by footsteps sounds from neighbours in heavy-weight concrete buildings and demonstrated that greater noise levels led to greater negative emotions. Recently, the impact of indoor acoustics environment on emotions was introduced as a gap in knowledge of research in indoor soundscapes [35]. In particular, still, there has been little attempt to investigate the emotional responses to indoor neighbour sounds using affective metrics and physiological responses [48]. Furthermore, there are growing demands for sustainable buildings and lightweight constructions, generating new living scenarios and indoor soundscapes; however, there is a lack of knowledge regarding the possible effect of neighbour sounds commonly heard in wooden residential buildings on the emotions and physiological responses of residents.Thus, the present study set out to investigate the emotions and physiological responses elicited by neighbour sounds in wooden residential buildings. A laboratory experiment was performed in an audiometric booth with neighbour sound from upstairs (i.e. footsteps sounds) and side units (i.e. speech and music). Firstly, the aim was to identify what kinds of emotional and physiological responses are evoked by neighbours sounds. Specifically, it was hypothesised that SPL and the types of sound sources might have an impact on affective and physiological responses. The second aim was to examine whether footsteps sound in isolation and footsteps sound combined with speech or music elicit different affective and physiological responses. Thirdly, it was hypothesised that affective and physiological responses to neighbour sounds might be influenced by participants’ noise sensitivity. Therefore, the participants were classified into two groups based on their self-rated noise sensitivity. Findings of this study may help to draw future acoustic regulation on indoor soundscape, relying on emotions and physiological responses of residents.

2. Methodology

2.1 Participants

A total of 41 participants (21 males and 20 females) aged from 20 to 40 (median=28 and std=4.4) took part in the experiment. The participants were recruited through the study advertisement after receiving ethics approval from the School of the Arts Ethics Committee at the University of Liverpool on the 8th of May 2019 (reference number:5233). Among people who had an interest in this study, only those who had self-reported normal hearing without any history of hearing, cardiovascular, respiratory, musculoskeletal, and stress/panic-related psychiatric health problems were recruited.

Before the start of the experiment, participants' noise sensitivity was evaluated using a 35-items questionnaire NoiSeQ [51], and participants were then divided into high and low noise sensitivity groups according to their overall noise sensitivity score. The NoiSeQ questionnaire was selected due to its proven ability to determine individual's noise sensitivity in a single administration, for being gender and age independent and due to its reported reliability [51, 52]. In order to observe a clear difference between the low and high noise sensitivity groups, participants with moderate noise sensitivity levels were excluded from the grouping. First, participants' noise sensitivity scores were divided into five groups using 20th, 40th, 60th, and 80th percentiles from the observed mean score distributions as cut-off points. Second, the middle range between the 40th and 60th percentiles was excluded. Thus, the 15 participants who scored below the 40th percentile were classified as the 'low noise-sensitivity group' (median=49 and std=8.6), while the 16 participants who scored above the 60th percentile were classified as the 'high noise-sensitivity group' (median=67 and std=4.7).

2.2 Sound stimuli

Four different sound sources were selected as representative of impact and airborne sounds which are most frequently heard in residential buildings as reported in previous investigations [44, 53-59]. Two of them are impact sounds: an adult walking (at two different paces: normal, 1.8 s^{-1} and fast, 2.2 s^{-1}) and a child running. The other two are airborne sounds: speech (a conversation between two people) and music (a piece of classical music played on the piano). Footsteps sound were recorded in a laboratory equipped with a timber floor separating vertically adjacent rooms [60]. During the recordings, the reverberation time was adjusted to about 0.5 s in the frequency range between 50 and 5 k Hz to demonstrate a furnished dwelling. Sound recordings of footsteps were performed with four different floor configurations: 1) bare timber joists with chipboard on top; 2) bare timber joists and chipboard with sand floating floor installed; 3) bare timber joists and chipboard with suspended ceiling, and 4) bare timber joists with chipboard, suspended ceiling and sand floating floor installed. For each configuration, recordings were repeated with and without a carpet finish. A binaural head equipped with two half-inch microphones (Type 40HL, GRAS) was used to record footsteps sound in the receiving room, while adults and children walked or ran diagonally in the source room. Most footsteps sound stimuli had dominant sound energies at low frequencies below 100 Hz. However, several sounds also showed strong sound energies at high frequencies because those were recorded on floor structures without floating floor or carpet. The airborne sounds (i.e., speech and music) were anechoic recordings. To simulate attenuation due to vertical partitions, three lightweight walls with good (R_w=52 dB), medium (R_w=43 dB), and poor (R_w=33 dB) sound reduction indices were applied to the recordings. The spectral characteristics of the airborne sounds were adjusted using the graphic equalizer of ‘Audition 3.0’ (Adobe). The sound stimuli used in this study are identical to those in a previous study [61] and frequency characteristics of the stimuli can be found in Figure S1 of the Supplement

2.3 Experimental design

The experiment consisted of four sessions: the first session for the evaluation of individual sounds and the others for the evaluation of combined sounds. In the first session, the affective reactions to individual sounds (footsteps, speech, and music) were assessed, while affective reactions evoked by footsteps sounds combined with speech or music were evaluated in the other sessions. Table 1 shows the sound pressure levels (SPLs) of selected sound stimuli. The SPLs of footsteps were based on the sound recordings and the ranges in SPLs of airborne sounds were determined assuming that the A-weighted equivalent sound pressure level (L_{Aeq}) of the speech and music were 79 and 80 dB, respectively, in the neighbour's houses. Thus, the A-weighted maximum sound pressure levels (L_{AFmax}) of the adult walking ranged from 30 to 50 dB with an interval of 5 dB, while the child running's L_{AFmax} is between 35 and 50 dB. In terms of L_{Aeq}, the filtered speech and music sounds varied from 24 to 42 dB and from 25 to 44 dB, respectively.

Table 1

2.4 Psycho-physiological responses

The 9-point Self-Assessment Manikin (SAM) scale [62] was used to directly measure the emotional response elicited by the sound stimuli in terms of arousal and valence. As shown in Figure 1, the arousal scale ranges from a calm figure to an excited one, while the valence scale shows SAM smiling at the right end and frowning at the left at the left. The 9-point scale was selected to enable a fine sampling of responses across the excitement and pleasantness dimensions. Before the listening test, participants were invited to familiarise themselves with the use of the SAM pictographic scales through a short explanation and a training session of approximately five minutes.

Figure 1

In the present study, four physiological measures were used: 1) fEMG expressed in microvolts (μV), 2) heart rate (HR) expressed in beats per minute (BPM) and 3) electrodermal activity (EDA) expressed in micro-Siemens (mS). All the physiological responses were recorded on a laboratory computer using a MP 150 WSW digital acquisition system (BIOPAC Systems) and were analysed using 'AcqKnowledge 4.4' (BIOPAC Systems). Three wireless amplifiers, placed on a desk, received all the data from the recording units via the operation of a Bluetooth transmitting mode. The fEMG activities in the corrugator supercilii (CS) and zygomaticus major (ZM) muscle groups were monitored throughout the experiment with four mm standard silver/silver chloride electrodes. Sensors were placed on the left side of the face as the right brain hemisphere is predominantly involved in spontaneous emotional reactions (contralateral motor control) [63]. To improve the quality of the fEMG signals, the participant’s skin was prepared by gently rubbing it with a skin preparation gel in the areas where the sensors were placed. The impedance level of the skin was examined to ensure that it was low enough for the signals collection (< 5kΩ) before the start of each listening test. The HR was gathered from the raw data of the oximeter, which was placed on the left hand’s ring finger. The EDA was measured using electrodes attached to the participant's index finger and middle finger of the left hand. All the data were visually inspected offline to detect artefacts and fEMG data were subjected to a square-root transformation. The participant's responses varied during baseline and sound exposure; therefore, the percentage change (%) was calculated to adjust all the different values [64]. The mean percentage change was defined as the percentage of change from the baseline to sound exposure. For the fEMG and EDA, the mean percentage change was computed between activity during the 6 s stimulus period and the 1 s immediately before stimulus presentation [12, 20]. For the HR, the mean percentage change was computed between activity during the whole 20 s stimulus period and the 10 s baseline [29].

2.5 Procedure

Upon arrival to the laboratory, a participant information sheet and a written consent form were provided to the participants, and only those who provided their consent participated in the study. Participants were equipped with all the sensors for the physiological measurements. The experiment took place in an audiometric booth with a low background noise level. Participants sat on a comfortable chair and were asked to answer the questionnaire through a graphic user interface (GUI) in Visual Basic presented on a monitor. The stimuli were presented diotically through headphones (DT 770 Pro) and through a subwoofer (SONAB System 9 CSW-71000) which was placed in front of the participants. White noise (NC-25) was presented through headphones throughout the experiment as ambient noise in the living room. Every session consisted of the following sequence, which was repeated for each sound stimulus: 1) participants were exposed to a 10 s baseline with white noise and a dark grey screen, then 2) the sound stimulus was presented for 20 s with a picture of a living room on the monitor, and finally 3) participants were given 10 s to rate arousal and valence on the 9-point pictorial scales (SAM). The duration of sound stimuli was decided upon ecological reasons [58], and to cover the full path (i.e. back and forth) on the floor sample installed in the building acoustic laboratory, while the duration of baseline was decided upon previous studies [16, 27, 28, 33]. There were breaks between sessions to avoid excessive fatigue and loss of concentration from the participants. In the individual sound session, which lasted 15 minutes, impact and airborne sound sources were presented singularly. In the remaining sessions, which lasted 21 minutes each, impact sounds were presented simultaneously with airborne ones. The outline of the listening test is illustrated in Figure 2. All sound sources and sessions were randomised across participants to avoid order effects. A training session of five minutes was designed to help participants to familiarise themselves with the sound stimuli and questionnaire and to check that all sensors were collecting data properly. During the experiments, participants were asked to imagine that they were relaxing in their homes while sounds were coming from neighbouring units.

Figure 2

2.6 Data analysis

During the physiological measurements, there were missing data in one or more measures due to equipment or recording errors. Thus, the numbers of participants for data analyses were different across the physiological measures: n=41 for fEMGs, n=40 for HR and n=29 for EDA. Statistical analyses were performed using ‘SPSS’ for Windows (version 26, SPSS Inc. Chicago, IL). Shapiro-Wilk normality test showed that all the data were normally distributed except for the data of the low and high noise-sensitivity groups. Thus, parametric tests were used for the majority of statistical analyses. Independent samples *t*-tests were conducted to estimate the significance of the differences in arousal and valence ratings between 1) impact source types, 2) individual and combined sound sources and 3) the differences in the physiological responses between individual and combined sound sources. Analysis of variance (ANOVA) was used to investigate the effects of sound sources type and levels on affective ratings and physiological responses. Pearson’s correlation coefficients were computed between 1) arousal and valence for the different sound sources and 2) affective ratings and physiological responses. Non-parametric test (Kruskal-Wallis test) was carried out to examine the differences between two noise-sensitivity groups in terms of affective ratings and physiological responses.

3. Results

3.1 Affective responses

Figure 3 shows the affective response to individual and combined sounds in terms of pleasantness and arousal with indication of the appetitive and defensive motivation circuits. The appetitive motivation organises response to stimuli promoting survival (e.g., food), while the defensive motivation mediates reaction to threat (e.g., natural disaster) [65]. For the individual sounds, the arousal ratings widely varied across the sounds stimuli, with a highest rating of 7.1 ± 1.9 (adult walking with a fast pace at 55 dB) and a lowest rating of 2.0 ± 1.0 (adult walking with a normal pace at 30 dB). The valence ratings were slightly less varied, ranging from 6.1 ± 1.5 (music through good performing partition) to 1.8 ± 1.1 (adult walking with a fast pace at 55 dB). More specifically, footsteps sound had greater variations in arousal (from 2.0 ± 1.0 to 7.1 ± 1.9) and valence (from 1.8 ± 1.1 to 5.5 ± 1.3) than speech (arousal from 2.4 ± 1.4 to 5.5 ± 1.9 and valence from 3.0 ± 1.5 to 5.2 ± 1.4) and music (arousal from 2.2 ± 1.4 to 3.1 ± 1.8 and valence from 5.3 ± 2.0 to 6.1 ± 1.5). For the sounds heard in combination, arousal ratings varied between 7.7 ± 1.7 (adult walking with a fast pace at 55 dB combined with speech through poor partition) and 1.9 ± 1.0 (adult walking with a normal pace at 30 dB combined with music through good partition). The valence ratings varied between 5.7 ± 1.3 (adult walking with a normal pace at 30 dB combined with music through good partition) and 1.6 ± 0.8 (adult walking with a fast pace at 55 dB combined with speech through poor partition). The majority of sounds were aligned along the defensive motivation circuit, but music sounds were closer to the appetitive motivation circuit. The correlation coefficients between the ratings of valence and arousal for individual impact and airborne sounds were significant (r=-.744, p<0.01 for impact and r=-.712, p<0.01 for airborne), indicating that more pleasant sounds tend to be less arousing. Similarly, combined sounds also had significant correlation coefficients between the arousal and valence ratings (r= -.739, p<0.01).

Figure 3

The affective ratings for the adult's walking were not significantly influenced by the pace of the walker [F (1,982) =.043, (p =.835)]. In addition, the differences in ratings between adult walking and child running were not statistically significant. Therefore, the averaged ratings across the walking pace and types of footsteps (adult and child) were used in the later analyses. Figure 4 represents the affective ratings of individual and combined sounds across different partitions as a function of L_{AFmax}. The affective ratings of individual footsteps sounds increased with an increase in SPLs. Arousal ratings varied between 1.9 ± 1.0 and 3.2 ± 1.8 for the SPLs of 30-35 dB, corresponding to the footsteps sounds recorded from the floor structure with a floating floor and suspended ceiling (i.e. good sound insulation performance). The ratings then increased up to 7.1 ± 2.0 at L_{AFmax}=55 dB (basic structure). Similarly, the valence assessments were significantly influenced by the SPLs but showed an opposite tendency. For 30-35 dB, the valence ratings were almost neutral, ranging between 5.5 ± 1.3 and 4.4 ± 1.6, while the rating was the lowest (1.9 ± 1.0) at 55 dB. The ANOVA result indicated that SPL has a significant effect on both arousal [F (5,650) = 89.611, (p<0.01)] and valence [F (5,650) = 80.980, (p<0.01)] ratings of individual footstep sounds. Regarding the individual airborne sources, ANOVA confirmed that the sound pressure level had a significant effect on both arousal and valence ratings for speech [F (2,120) = 30.849, (p<0.01)], [F (2,120) = 28.134, (p<0.01)], but not for the music clip [F (2,120) = 2.835, (p=0.063)], [F (2,120) = 2.677, (p=0.073)].

Similar patterns of affective ratings were observed from the combined sounds; however, there were slight differences in the ratings across the sound insulation performance of the vertical partitions and types of airborne sounds. There were significant changes in affective ratings of the combined sounds with the addition of speech, in the region of 24 and 42 dB (L_{Aeq}) through different partitions. The arousal ratings increased from 2.37 ± 1.4 to 5.5 ± 1.9, whereas the valence ratings decreased from

5.2 ± 1.4 to 3.0 ± 1.5. In contrast, the addition of music to the footsteps sounds did not lead to significant changes in affective ratings, especially for arousal judgments. The arousal ratings ranged between 2.2 ± 6.1 and 3.1 ± 5.3, while the valence ratings varied from 5.3 ± 2.1 to 6.1 ± 1.5. The results of ANOVA confirmed that the SPL had a significant effect on both arousal [F (2,120) = 30.849, (p<0.01)] and valence ratings [F (2,120) = 28.134, (p<0.01)] for footsteps combined with speech, but not for footsteps combined with music ([F (2,120) = 2.835, (p=0.063)] for arousal and [F (2,120) = 2.677, (p=0.073)] for valence).

The affective ratings in Figure 4 can be compared across the sound insulation performance of the partitions and airborne sound types. Overall, the effects of the airborne sources on both arousal and valence were stronger for the better floor structures (L_{AFmax} of 30-35 dB), whereas the addition of the airborne sources became less effective for the better wall partitions. A series of *t*-tests were conducted to compare the affective ratings of individual and combined sounds at the same SPLs. As shown in Figure 4, significant differences occurred mainly for footsteps in combination with speech; fewer significant differences were found for footsteps combined with music. For footsteps sounds presented with speech through the poor partition (R_{w}=33 dB), affective ratings were always significantly different from those of individual sounds for the whole range of SPLs (except for valence at 55 dB). For footsteps heard in combination with speech through the medium partition (R_{w}=43 dB), the affective ratings significantly changed only in the region of 30 and 45 dB. Few significant differences were found when footsteps were heard singularly or in combination with speech through the good vertical partition (R_{w}=52 dB).

Figure 4

3.2 Physiological responses

Figure 5 shows the mean changes in fEMG of the corrugator supercilii (CS) and the zygomaticus major (ZM) muscles groups averaged across the 41 participants. As plotted in Figure 5(a), fEMG CS increased during the presentation of individual sounds except for music. Specifically, during the exposures to footsteps sounds (adult walking and child running) and speech, the fEMG CS increased by 0.20% and 0.22%, respectively. The fEMG ZM, which is generally associated with positive emotions, decreased by 0.22% with the presentations of individual footsteps; however, smaller changes were found for speech and music. In general, footsteps sounds generated larger changes in the fEMGs than airborne sounds; however, the differences in the activity of the two muscle groups were not statistically significant. In addition, two different airborne sources showed different tendencies in the fEMGs due to their different characteristics. The responses to the combined sound sources are presented in Figure 5(b). The responses to individual footsteps sounds averaged across adult walking and child running were plotted as a reference. Similar results were found from the analysis of responses to combined sound sources; the fEMG CS increased and the fEMG ZM decreased during the exposures to the combined sound sources. More specifically, listening to the footsteps sounds in combination with speech or music led to increases of the fEMG CS by 0.12% and 0.14%, respectively. These changes were slightly lower than the changes due to the exposure to the individual footsteps sounds; however, the differences between them were not statistically different. Similarly, adding airborne sources to the footsteps sounds reduced the changes in the ZM. The *t*-tests confirmed that those changes were significantly different from the responses to the averaged individual sounds ($p<0.05$ for speech and $p<0.01$ for music).

Figure 5

Figure 6 shows the relationships between SPLs and fEMGs in response to individual and combined sounds. For individual impact sounds, fEMG CS activities increased except for adult walking at 55 dB, but those fluctuated a great deal with SPLs. Most fEMG ZM activities decreased but there was no strong trend along with SPLs. On the other hand for individual airborne sources, fEMG CS and fEMG ZM decreased with an increase in SPL for both music and speech. In particular, fEMG ZM was significantly correlated with SPLs of airborne sources (r=-.178, $p<0.05$ for speech and r=-.209, $p<0.05$ for music). Similar patterns were found from the combined sound sources. The fEMG CS increased after the exposure to most combined sound sources, but there was no strong tendency with varying SPLs. The fEMG ZM activities were fluctuated a great deal across SPLs and sound sources after adding airborne sounds. The correlation coefficients between SPLs and fEMGs were not significant for combined sound sources.

Figure 6

Correlations coefficients between affective ratings and fEMG responses were computed across all the sound stimuli. A significant correlation was found between arousal ratings and fEMG CS (r=-0.29, $p<0.05$); however, other correlations were not statistically significant. For further investigation, the participants were classified into three groups based on arousal ratings: Group 1 (arousal ratings from 1 to 3), Group 2 (arousal ratings from 4 to 6) and Group 3 (arousal ratings from 7 to 9). The results of one-way ANOVA indicated that the three groups had a significant impact on the fEMG CS [F (2,4835) = 4.449, ($p<0.05$)]. *Post hoc* comparisons via Tukey's test confirmed that the difference in the fEMG CS between Group 1 and Group 2 was significant ($p<0.01$).

Changes in heart rate (HR) were averaged for all the participants, and the mean changes are presented in Figure 7. Overall, the mean HR decreased by more than 2% for both impact and airborne sounds and the differences between the baseline and the stimulus exposure were statistically significant ($p<0.05$ for all). In particular, listening to footsteps of the child running led to the highest decrease in HR, which is significantly greater than the changes due to the adult walking ($^{*}p<0.05$). The mean HR changes due to the combined sound sources are presented in Figure 7(b) along with the mean changes due to averaged individual footsteps sounds. The mean HR changes of the averaged combined sound sources were similar to those of the invidivual footstep sounds with decreases of more than 2%, and the differences between the individual and combined sound sources were not statistically significant. This implies that the addition of airborne sources to footsteps sounds has little impact on the mean changes in HR. Contrary to the fEMGs, no significant correlations were found between affective ratings and the mean HR.

Figure 7

Figure 8 represents the effects of SPL on HR in response to individual and combined sounds. The HR decreased while listening to individual footsteps sounds. In particular, HR decreased with increasing SPL in the range between 40 and 55 dB for the adult walking. However, this trend was not found at lower SPLs for the adult walking, and the HR changes were not much changed for the child running. For individual airborne sources, HR also decreased for all the SPLs, but there was not a clear relationship between the HR and SPLs. For combined sound sources, the HR increased after exposure to most combined sound sources with an increase in SPL for either music or speech. However, correlations coefficients between HR and SPL were not significant for both individual and combined sound sources.

Figure 8

Figure 9 shows the mean changes in EDA from baseline to stimulus presentation. Similarly to HR, the mean percentage EDA change decreased compared to baseline for all the sound sources. The decrease of the mean percentage EDA due to individual sounds ranged between -0.69% (adult walking) and -0.56% (speech), as shown in Figure 9(a). The mean percentage EDA changes of combined sounds were similar regardless of the airborne source types (speech: decrease by 0.60% and music: decrease by 0.57%). Source type also caused some significant changes in the mean percentage change of EDA for combined sounds with music through the poor partition (R_w=33 dB) for adult walking and child running. Furthermore, significant differences (p<0.01) were found for footsteps sounds in isolation or in combination with speech through the good partition (R_w=52 dB) and music through the poor partition (R_w=33 dB). Correlations coefficients between affective ratings and the mean EDA were computed, and only one significant correlation was identified between valence rating and the mean percentage change of EDA (r=-.040, p<0.05).

Figure 9

Figure 10 shows the effects of SPL on EDA in response to individual and combined sounds. For individual adult walking footsteps, an increase of EDA with SPL was identified, whereas there was no consistent trend between EDA and SPL for the child running. For individual airborne sources, mean changes in EDA were quite similar, except for music at 44 dB. The correlation coefficient between EDA and SPLs of individual sounds was significant (r=.076, p<0.05). The EDA changes recorded after exposure to footsteps combined with speech were not influenced by SPLs, whereas the ones recorded after exposure to footsteps combined with music increased with SPL. However, correlations coefficients between the EDA and SPLs were not significant for combined sound sources.

Figure 10

3.6 Effect of noise sensitivity on affective and physiological responses

Kruskal-Willis non-parametric tests were carried out to assess the significance in differences in arousal and valence ratings for individual and combined sound sources between low and high noise sensitivity groups. Across the sound sources heard singularly, footsteps showed several significant differences between the groups as shown in Figure 11. However, no significant differences were found in the arousal and valence ratings of the airborne sources despite their variation in SPL. When listening to footsteps sounds individually, arousal ratings showed more significant differences between two groups than valence ratings. Particularly, the high noise-sensitivity group showed greater arousal ratings than the low noise-sensitivity group, and the differences between them were significant at five SPLs. On the other hand, the high noise-sensitivity group had lower valence ratings than the low noise-sensitivity group, and significant differences were found at three SPLs (45, 50 and 55 dB). For combined sound sources, a total of 50 significant differences in arousal ratings were found among 96 combinations across different partitions and airborne sound sources. More specifically, more significant differences in arousal ratings were found for combined sounds through the medium and poor partitions. In contrast, only 12 combinations showed significant differences in valence ratings between low and high noise-sensitivity groups. Comparisons of low and high noise-sensitivity groups for all the combined sound sources with different partitions and airborne sound sources can be found in the Supplementary Table S1. Similarly, the physiological responses to footsteps (individual and combined), speech and music were compared across two noise-sensitivity groups via Kruskal-Willis non-parametric tests. Contrary to the affective ratings, there were no statistically significant differences in any of the physiological responses. More details can be found in the Supplement Figures S2 and S3.

Figure 11

4. Discussions

4.1 Affective ratings

Most previous studies on the affective ratings of acoustic stimuli have investigated everyday sounds that are frequently heard in people’s daily lives [13, 15, 17, 66]. In particular, Bradley and Lang [17] used various sounds such as bird singing, roller coaster, tick of a clock and baby crying. The present study evaluated the affective ratings of impact footsteps sounds individually and in combination with airborne sources; thus, the results are comparable with the previous study [13]. Most footsteps sounds used in the present study were less exciting than roller coaster and baby crying sounds [17] in terms of arousal. However, an increase in SPL significanlty affected arousal ratings of footsteps, making them comparable to different sounds. For example, footsteps sounds at 30-35 dB corresponded to the cardinal singing, while those at 55 dB were similar to the roller coaster sound [17]. Similarly, the valence ratings of the footsteps sounds varied with increasing SPLs in the present study; thus, the corresponding sounds of the previous study [17] were different across the SPL. For example, the footsteps sounds at 30 dB were similar to the rating for the natural sound from cows, but the same sounds at 50 dB corresponded to the rating for a baby crying. This indicates that the SPL of the footsteps sounds is an important factor affecting affective reactions.

The International Affective Digitalised Sounds (IADS) [66] classified the walking sound (valence: 4.15 ± 1.28 and arousal: 5.43 ± 1.9) as neutral. This classification was also confirmed in the expanded version of the International Affective Digitalized Sounds (IADS-E) [15], which included four walking sounds with varied ratings (arousal: 4.17 ± 2.04 to 5.45 ± 1.37 and valence: 4.73 ± 0.61 to 5.42 ± 1.27). In general, the ranges of affective ratings of IADS and IADS-E were much narrower compared to the sounds included in the present study (arousal: 2.0 ± 1.0 to 7.1 ± 1.9 and valence: 1.8

± 1.1 to 5.5 ± 1.3). This disagreement may be attributed to the differences in the setting and environment where the sounds were recorded and heard. Both the IADS and IADS-E recorded the walking sounds when both the source and the receiver were in the same room; however, in the present study, a source was located in an upper room and a receiver was in the room below to represent the noise from neighbours. More recently, Tajadura-Jiménez et al. [13] explored affective responses to approaching and receding footsteps. They reported valence ratings for the sound stimuli with varied SPLs from 68 to 86 dB (L_{Aeq}). The valence ratings of the approaching and receding footsteps sounds were similar to those of the adult walking at 35-40 dB (L_{AFmax}) in the present study. As with the IADS and IADS-E, the huge difference in SPL for the similar valence ratings could be because Tajadura-Jiménez et al. [13] recorded the footsteps sounds with both the source and receiver located in the same room. While there are a number of studies about annoyance from floor impact sounds, there has been little attempt to explore emotional responses to footsteps; thus, future studies are required to understand the affective response to footsteps sounds with different characteristics.

The present study highlighted the fact that the emotional reactions to footsteps sounds and speech from neighbours were greatly influenced by the SPLs of the stimuli. These results are consistent with the findings of Yang et al. [15] in which the relationships between affective ratings (arousal and valence) and the peak intensity (L_{Amax}) were significant across 935 sounds ranging between 54 and 88 dB. Yang et al. [15] also demonstrated that physically intense sounds were highly arousing, causing a fear response, but the relationship between the physical intensity of the sound and valence was more complex than for arousal. This is partially confirmed by our findings, as the SPLs showed a significant correlation with negative-valence stimuli (i.e footsteps and speech), but there was no significant correlation for the only positive-valence stimuli (i.e. music). Similarly, Bradley and Lang [17] reported that there was a positive and significant correlation between arousal ratings and peak sound intensity of 60 everyday sounds, but there was no correlation between valence and peak sound intensity. In order to enhance understanding of affective ratings, sound quality (SQ) metrics (*loudness*, *fluctuation strength*, *sharpness* and *roughness*) were analysed. The SQ metrics were computed using ‘BK Connect’ (Brüel & Kjær). *Loudness* was calculated according to ISO 532–1, which describes the procedures for calculating the time-varying loudness. During the calculation of *sharpness*, *roughness* and *fluctuation strength*, the time interval between the spectra was set at 2 ms. Pearson correlating coefficients were then computed between SQ metrics and affective ratings for all the sound stimuli, single and combined sound sources. As listed in Table 2, affective ratings were significantly correlated with *loudness*, *fluctuation strength* and *roughness*. *Fluctuation strength* describes the fluctuation of the signal, while *roughness* indicates the human perception of temporal variation of sounds. This indicates that affective ratings were influenced by temporal variations as well as sound pressure levels. This finding shows a good agreement with previous studies [67, 68] which reported that annoyance ratings of footsteps sounds were correlated with *loudness, roughness* and *fluctuation strength*. On the other hand, the relationships between affective ratings and *sharpness* were not significant. This might be because the frequency characteristics of the stimuli were similar along with dominant energy at low frequencies; thus, *sharpness* was not varied widely.

Table 2

Previous research has shown how affective reactions to auditory stimuli tend to align along two motivational circuits, creating a boomerang-like shape [13, 15, 17]. Bradley and Lang [17] found that sound sources such as cows, sailing and erotica align along the appetitive motivation circuit, whereas a clock ticking, a baby crying, and a weapon burst align along the defensive motivation circuit. These findings were afterwards extended and confirmed by Yang et al. [15]. Tajadura-Jiménez et al. [13] identified the activation of the defensive motivation circuit from approaching and receding footsteps sounds with various SPLs. They concluded that the variation of speed at which the sound source is approaching or receding (1 s, 2 s or 3 s ramp) aligns along the defensive motivation circuit, indicating that sound sources moving faster towards the participants elicited a more fearful responses. The affective ratings of the present study aligned along a half-boomerang-like shape. In particular, the ratings of floor impact sounds, both individually and in combination with speech or with music and individual speech mostly overlapped with the defensive motivation circuit. These findings suggest that common neighbour noises heard in wooden buildings elicit the activation of a neural circuit which mediates reactions to threat [65]. On the other hand, the music showed a mild activation of the appetitive motivation circuit. However, the music clip used in the present study was a piece of classical music played on the piano, which is less annoying than other neighbour sounds; thus, it does not represent other, potentially annoying, music sounds from neighbours. Instrumental music was also used in a previous study on indoor soundscape [47] and it was shown that indoor soundscape was perceived as more annoying with fan noise and more comfortable with music. Moreover, previous studies reported that valence and arousal ratings were significantly varied across music clips with different styles and genres [15, 16], suggesting that further study is required to investigate affective reaction to various music clips heard from neighbours. Similarly, emotional reactions to different verbal speech including voice-AI systems [69] also can be explored in the future as suggested by Erickson et al. [70]. In addition, the inclusion of informational properties of sounds (i.e. sound categories) sensibly improved Comfort predictability in another investigation [47], confirming the important contribution of semantic features of sounds (e.g. sound type) in soundscape evaluations [71]. It is well-known that lightweight wooden structures as more sustainable than heavyweight structures such as concrete. Acoustic properties of wooden materials and building elements such as floor and wall have been widely examined through laboratory and field measurements [72-77]. On the other hand, there is still a lack of understanding as to how neighbour sounds transmitted through lightweight wooden building elements affect residents' subjective reactions. Compared to heavyweight buildings, only very few studies explored the people's reaction to building noise in lightweight structures. For example, a comparison of a concrete and a wooden building with the same floor impact sound insulation performance [78] indicated that the wooden building had serious complaints from the inhabitants, but it was not the case for the concrete construction. Also, lightweight floor structures were more annoying than heavyweight concrete floor structures for the same weighted floor impact sound levels [79, 80]. The current study extended the current knowledge of people's reactions to neighbour sound in lightweight structures in terms of affective ratings;

however, additional research is required to fully understand how emotions are developed and varied in different settings.

4.2 Physiological responses

The laboratory experiment revealed that exposure to individual and combined sounds from neighbours in wooden buildings caused detectable changes in physiological responses. More specifically, exposure to neighbour sounds led to increased fEMG CS activity and, decreased fEMG ZM activity together with a decrease in HR and EDA. However, there were a few exceptions from the airborne sound sources: a decrease in fEMG CS activity for exposure to the music clip and an increase in fEMG ZM activity when listening to speech. These results are consistent with previous studies in the auditory domain in terms of fEMG [17, 25, 81], HR [27-29] and EDA [82]. The increased fEMG CS activity and decreased fEMG ZM activity are generally caused by unpleasant and negative stimuli [17, 25, 26, 63, 81]. Thus, the results of the fEMG suggest that sounds from neighbours, especially footsteps, may generate adverse reactions in residents. In addition, the results showed that the individual footsteps sounds caused the largest increase in the fEMG CS activity and the largest decrease in the fEMG ZM activity. Furthermore, the addition of airborne sources to footsteps sounds reduced the activity of both muscle groups monitored by the fEMG. However, the fEMG activities can also be changed by non-emotional gestures. For example, lowering and raising the brows are associated with the biological function of decreasing or increasing the visual input [83] rather than emotion. But the fEMG activities by the brows movements might be much less than those by the sound stimuli in the present study. Nevertheless, it would be worth investigating how sound stimuli evoke the brows movements which lead to changes in fEMG activities in the future.

A decrease in HR was found in this study like in other studies with those who were exposed to auditory stimuli [17, 27-29]. This finding agrees with the previously reported results in other sensory fields [84, 85] and can be explained by Laceys' model [86], which describes the effect of attention on heart rate. According to Laceys' theory of intake and rejection, the deceleration of heart rate occurs due to the diversion of attention to an external task such as perception of a visual or auditory stimulus. On the other hand, when the attention must be focused on an internal task and the environment must be rejected, heart rate tends to accelerate. Previous investigations have also pointed out larger deactivation for less pleasant acoustic stimuli or soundscapes [19, 27, 28, 87, 88]. In the present study, the largest fall in HR was recorded when footsteps from a child running were presented and this was significantly larger than decreases in HR produced by adults walking. This suggests that footsteps sound from a child running were significantly less preferred than the other neighbour sounds such as adult walking, speech and music.

The EDA response decreased during stimuli presentation in the present study. However, Park and Lee [29] reported an increase in EDA while participants were exposed to footsteps sound (adult walking and child running) recorded in heavyweight buildings. The decrease in EDA activity in this study may be related to the physiological habituation of participants. Glass et al. [89] reported EDA habituation in almost 90% of their participants, while only 4% seemed to be unable to adapt physiologically during a listening test. In the current study, the majority of sounds were footsteps and this may have accentuated the habituation effects. Other researchers, who investigated sound sources that contrasted more with one another, have also demonstrated a decrease in EDA. For instance, Tajadura-Jiménez et al. [90] showed a decrease in EDA from a small simulated room with presentations of sounds (e.g., a dog growling) in front or at the back of the listener. It was also revealed that the EDA responses to individual and combined sound sources were significantly different ($p<0.01$) for some cases: 1) for footsteps heard singularly and in combination with speech through the good partition (R_w=52 dB) and 2) footsteps heard singularly and in combination with music through the poor partition (R_w=33 dB). This result may imply that the lower speech intelligibility through the good vertical partition and the clearer music through the poor partition contributed to the change in EDA responses.

For individual sounds, there were no significant differences in physiological responses across different sound sources except for HR changes in response to two types of footsteps. This might be because all the sounds were coming from neighbouring units, and thus, all the sources presented were associated with a similar image (i.e. neighbours), leading to small difference in physiological responses. Hearing a specific sound or music may automatically evoke images of the corresponding object or event, with the subject possibly imagining him - or herself as part of the scene [16], but sometimes people listen without generating mental images [91]. A previous investigation [16] reported substantial differences in HR and EDA across everyday sounds (e.g., cheering spectators at a sport event, ringing telephone or waterfall) or musical instrument excerpts. In the current study, all sounds were coming from neighbours so the participants might have had similar images during the experiment. This might be another reason for the non-significant differences in physiological responses to the sound stimuli in this study. The fEMG results are in line with previous research in which no significant difference was found in the activation of the two muscle groups when stimuli with mildly negative or neutral in terms of valence were presented [81]. However, significant differences were detected over fEMG ZM when footsteps were heard singularly or in combination with speech ($p<0.05$) or music ($p<0.01$). These findings may indicate that airborne sources moderate adverse reactions to floor impact sounds.

In the current study, the SPL had no significant effect on physiological responses except for the fEMG ZM of the music and the EDA of individual sounds. This finding agrees well with previous results [28] which revealed no relationships between SPLs and HR and fEMG CS when sounds' SPL varied between 60 and 74 dB. Similarly, Bradley and Lang [17] did not identify a significant effect of sound intensity on fEMGs and HR using stimuli ranging between 64 and 81 dB. Several studies [13, 92-94] reported significant correlations between SPLs and physiological responses, but they used much louder or longer sounds than the current study. For instance, Tajadura-Jiménez et al. [13] found a trend in the effect of intensity range of sounds (loud: 68 to 86 dB L_{Aeq} or soft: 50 to 68 dB L_{Aeq}) on fEMG CS, while other field studies [92-94] investigated long-term noise exposure effects and reported a significant effect of SPL on HR and EDA. This finding implies that the SPLs of neighbour sounds have no significant impact on residents' physiological responses in the ranges between 30 and

55 dB in a laboratory setting. However, it is still unknown if the residents' physiological response would be similar when presented with loud noise from outside such as transportation noise, or when experiencing long-term exposure; thus, further studies are required to see the effect of loud outdoor noise and long-term exposure in residential buildings. Previous investigations on emotions elicited by everyday sounds in residential buildings have relied on surveys and interviews [11, 44]. Few researchers have conducted laboratory studies with controlled sound exposure, but none of those collected affective ratings along with physiological responses [29, 42, 47]. Only recent outdoor soundscape studies have dealt with emotions and physiological responses together [19, 28, 34]. The current study assessed physiological responses (fEMGs, EDA, HR) as well as emotions to building noises in laboratory conditions, which offered a more holistic approach to residents' reactions to noise in newly promoted high-rise wooden buildings. A significant correlation was found between arousal and fEMG CS (r=-0.29, p<0.05), and this was also confirmed by ANOVA [F (2,4835) = 4.449, (p<0.05)] across three arousal groups. In contrast, no significant correlation between arousal and fEMG ZM or between valence and two fEMG activities was observed. This is not in agreement with previous research which identified significant correlations between fEMG activities and valence (i.e. more CS activity for unpleasant sounds and increasing ZM activity for increasing valence) [17, 81] but no correlation between arousal and two fEMG activities [17]. This inconsistency may be due to the different set of sound stimuli, which caused less variation in valence ratings in this study when compared to previous research. In the present study, participants were asked to imagine that they were relaxing at home while neighbour sounds were transmitted through the siding and upper units; thus, most sound stimuli showed low valence ratings (<6 on a 9-point scale). However, a significant correlation was identified between EDA and valence ratings (r=-.040, p<0.05) and the ANOVA also confirmed that the EDA responses were statistically different across three valence groups (Groups 1-3) [F (2,3899) = 2.619, (p = 0.073)]. Similarly, Bradley and Lang [17] reported that the EDA was modulated by high valence ratings after listening to pleasant or unpleasant sounds. In accordance with the present results, previous studies [16, 19] have demonstrated insignificant correlations between

EDA and widely varied arousal ratings after listening to everyday sounds. Furthermore, no significant correlations between affective ratings and HR were identified in the current dataset. Several studies have also failed to find any significant relationship between HR and arousal [17, 19, 95-97] or valence ratings [33], although high-arousal music led to higher HR compared to low-arousal music [98].

In the present study, arousal and valence ratings showed significant differences across noise sensitivity groups. This finding agrees with previous findings [42] which suggested noise sensitivity as a possible moderator in emotional responses, reporting that higher noise sensitivity would influence individuals' appraisals by causing them to perceive higher anger, dislike, and pain, whereas low noise sensitivity may lead to a more empathetic appraisal of the event. Conversely, there were no statistically significant differences in the physiological responses between the two noise-sensitivity groups. These results are consistent with previous research that dealt with the real impact sources in residential buildings [99] and sound sources with different emotional content [100]. In particular, Park [99] found that the relationship between noise sensitivity and the cardiac response was nonsignificant for unpleasant stimuli, suggesting that cardiac response is not related to self-rated noise sensitivity for stimuli eliciting negative emotional responses. However, for pleasant stimuli (i.e. music), a negative association between HR and noise sensitivity was found. The significance of the acoustic and physiological parameters used in the study was summarised in Table 3.

Table 3

4.3 Limitations and suggestions for further research

The major limitation of this study is a small pool of sound stimuli focusing on common neighbours noise, so there were no sounds that belong to affectively potent categories (e.g., crying, laughing, erotica). In addition, different floor materials, shoes and body sizes would change the characteristics of footsteps sound [101] and hence elicit different affective and physiological responses. Thus, it would be useful to examine the psycho-physiological responses evoked by more neighbour noises (e.g., chair/furniture scraping and washing machine [102]) and footsteps sound to present more realistic indoor soundscapes. Secondly, participants didn't engage or interact with anything during the experiment. Human emotions naturally occur in interaction with others and with external events [103], so the participants might have responded to the questionnaire as passive observers [104]. Therefore, there is a possibility that this study may have missed some important aspects related to the process of triggering emotions [104] and further consideration of methods for evoking emotional responses to neighbour's noise could be examined with more engagements and interactions [105]. Additionally, previous research has suggested that perceptual outcomes in soundscape domain were affected by participants' tasks or activity at hand in laboratory tests [48]. Xue et al. [106] also reported that people became more sensitive to the acoustic environment when engaging in low-intensity activities. Thirdly, the majority of participants gave positive feedback on the use of the living room pictures but some said it was quite different from a typical living room they have lived in or experienced. In the future, other methodology including virtual reality (VR) or simulated environment could be helpful to help participants immerse themselves more realistically into the situation. The inclusion of additional elements affecting the pleasantness of the visual environment could also be explored (e.g., greenery from the windows) as it has been correlated with pleasantness, eventfulness, and familiarity ratings of soundscape [107-109]. Fourthly, in the current study, the psychological and emotional states of the participants were not measured before taking part in the experiment. Previous research [15] used the Japanese version [110] of the State-Trait Anxiety Inventory [111] to identify the participants' psychological states when they participated in the experiments. This approach could be adopted in the future to better understand the participants' state before the start of the experiment. Similarly, more information on the average amount of time participants spends in their homes together with usage time patterns and cultural and social individual characteristics could be included as potential factors affecting soundscape judgements [36, 108]. Lastly, in the current investigation, the physiological responses of fEMG, HR, and EDA were used as indicators of listener state. In the future it would be informative to record electrical activity in the brain (EEG), allowing for acquisition of data directly from the scalp, even before other physiological responses are triggered. Possibly, monitoring the EEG activity in different part of the brain and in different hemispheres would allow a deeper understanding of the reactions to neighbour sounds and of their effect on the emotional state of the listeners.

5. Conclusions

The present study was designed to determine the effect of neighbour sounds on emotions and physiological responses. A listening test was performed with impact (footsteps from upstairs) and airborne sounds (speech and music from siding units) heard through floors and partition walls with different sound insulation performances. Individual sounds and footsteps sound in combination with speech or music were presented to participants. The participants were asked to rate arousal and valence of each stimulus. In addition, physiological responses were monitored in terms of fEMGs, HR and EDA. For both individual and combined sounds, arousal and valence ratings aligned along the defensive motivation circuit, suggesting that the affective responses to neighbour sounds are also organised between two motivational systems. Affective ratings were significantly influenced by the sound pressure level of sound sources except for individual music sounds and combined noise including music sounds. Additionally, for the combined sound sources, the contributions of airborne sounds to the affective ratings were stronger with floor structure with better sound insulation, but they became weaker with the partitions with better sound insulaton performance. However, the influences of the airborne sources on arousal and valence ratings became less effective for the wall partitions with better sound insulation performance. Moreover, the current study revealed that there are reliable patterns of physiological changes in fEMG, HR and EDA after exposures to both individual and combined sounds. Overall, exposure to neighbours sounds led to an increase in fEMG CS activity and a decrease in fEMG ZM activity, HR and EDA. However, a few exceptions were found in which fEMG CS activity decreased for the music and fEMG ZM activity increased for the speech. Significant differences in fEMG ZM activity between individual footsteps sound and combined sounds were identified, suggesting that combined sounds were preferred to individual footsteps sound. Sound pressure levels did not influence any of the physiological parameters except for fEMG

ZM (music) and EDA (individual sounds). Arousal ratings were significantly correlated with fEMG CS activity, while ratings of valence showed significant correlation with EDA. This implies that more arousing sounds generated greater fEMG CS activity and less pleasant sounds caused lower EDA response. Finally, our findings revealed that noise sensitivity had a significant effect on affective ratings of individual footsteps sound, but this was not the case for individual airborne sounds. Among 96 combinations of sounds, the low and high noise sensitivity groups showed significant differences in arousal ratings in 50 cases, while only 12 cases showed significant differences in valence ratings. In addition, physiological responses were not significantly different across the two noise sensitivity groups.

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Table 1. Sound stimuli and their overall SPLs (dB) in terms of L_{AFmax} for impact sound sources and in terms of L_{Aeq} for airborne sound sources. The SPLs of adult walking are the same for the normal and fast paces.

Adult walking	Child running	Speech	Music
30, 35, 40, 45, 50, and 55	35, 40, 45, and 50	24, 29 and 42	25, 29 and 44

Table 2. Correlation coefficients between psychoacoustics parameters and affective ratings ($^{*}p<0.05$ and $^{**}p<0.01$).

	Arousal				Valence			
	Loudness	Fluctuation Strength	Roughness	Sharpness	Loudness	Fluctuation Strength	Roughness	Sharpness
All	$.721^{**}$	$.653^{**}$	$.378^{**}$	-0.135	$-.634^{**}$	$-.596^{**}$	$-.341^{**}$	0.089
Single	$.817^{**}$	$.885^{**}$	$.636^{**}$	0.129	$-.714^{**}$	$-.829^{**}$	$-.442^{*}$	0.097
Combined	$.757^{**}$	$.856^{**}$	$.665^{**}$	0.018	$-.676^{**}$	$-.789^{**}$	$-.605^{**}$	-0.068

Table 3. Significance of the correlations between physiological parameters, affective ratings, and SPL.

	Arousal	Valence	SPL
fEMG CS	Significant (r= -0.29, $p<0.05$)	Non-significant	Non-significant
fEMG ZM	Non-significant	Non-significant	Significant for speech and music (r= -.178, $p<0.05$ and r= -.209, $p<0.05$)
HR	Non-significant	Non-significant	Non-significant
EDA	Non-significant	Significant (r= -.040, $p<0.05$)	Significant for single sound sources (r=.076, $p<0.05$)

Figure captions

Figure 2. Self-Assessment Manikin (SAM) 9-point scales for assessment of arousal (top) and valence (bottom).

Figure 2. An illustration of the outline of the listening experiment and of the composition of each stimulus presentation (the order of sessions was randomised).

Figure 3. Affective ratings of a) individual sounds and b) combined sounds with an indication of appetitive and defensive motivational circuits.

Figure 4. Affective ratings of individual footsteps sound and footsteps sound in combination with an airborne source across three partitions with different R_w: a) arousal ratings for individual footsteps and footsteps combined with speech, b) arousal ratings for individual footsteps and footsteps combined with music, c) valence ratings for individual footsteps and footsteps combined with speech and d) valence ratings for individual footsteps and footsteps combined with music (* $p<0.05$ ** $p<0.01$).

Figure 5. fEMG CS and fEMG ZM changes: a) individual sounds and b) combined sounds (* $p<0.05$ ** $p<0.01$).

Figure 6. fEMG CS and ZM changes across SPLs. a) CS and SPL of individual footsteps sounds, b) ZM and SPL of individual footsteps sounds, c) CS and SPL of individual airborne sounds, d) ZM and SPL of individual airborne sounds, e) CS and SPL of footsteps sounds combined with speech and f) ZM and SPL of footsteps sounds combined with speech, g) CS and SPL of footsteps sounds combined with music and h) ZM and SPL of footsteps sounds combined with music.

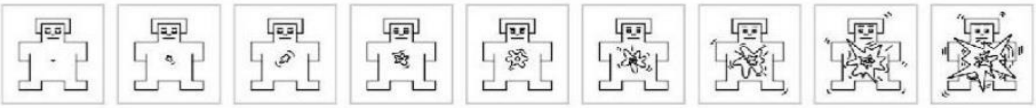
Figure 7. HR changes: a) individual sounds and b) combined sounds (*$p<0.05$).

Figure 8. HR changes and SPL: a) HR and SPL of individual footsteps sounds, b) HR and SPL of individual airborne sounds and c) HR and SPL of footsteps sounds combined with speech, and d) HR and SPL of footsteps sounds combined with music.

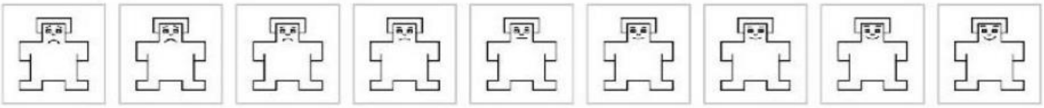
Figure 9. EDA changes: a) individual sounds and b) combined sounds.

Figure 10. EDA changes and SPL: a) EDA and SPL of individual footsteps sounds, b) EDA and SPL of individual airborne sounds and c) EDA and SPL of footsteps sounds combined with speech, and d) EDA and SPL of footsteps sounds combined with music.

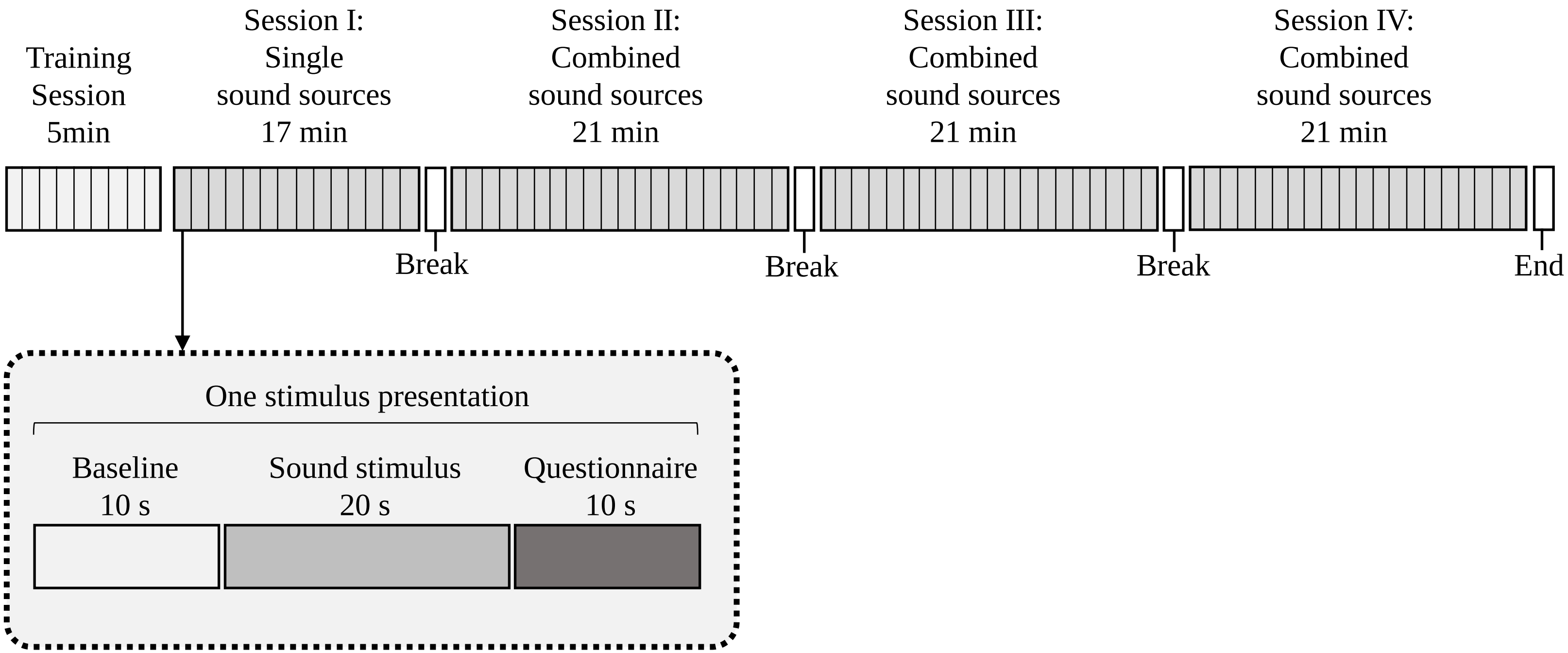
Figure 11. Affective ratings of individual footsteps sounds between the low and high noise-sensitivity groups; a) arousal and b) valence (* $p<0.05$ ** $p<0.01$).

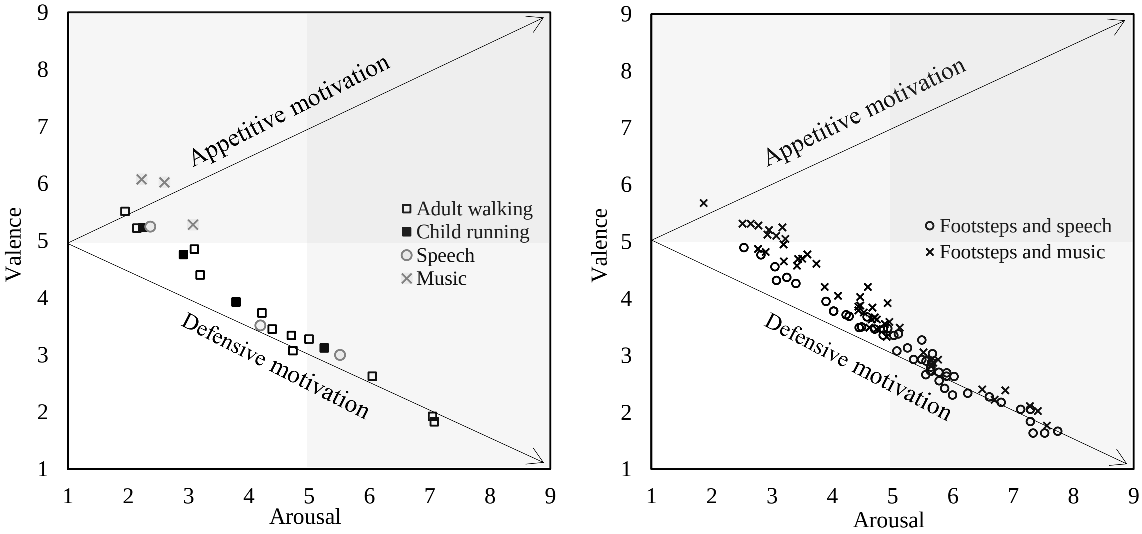


○ ○ ○ ○ ○ ○ ○ ○ ○

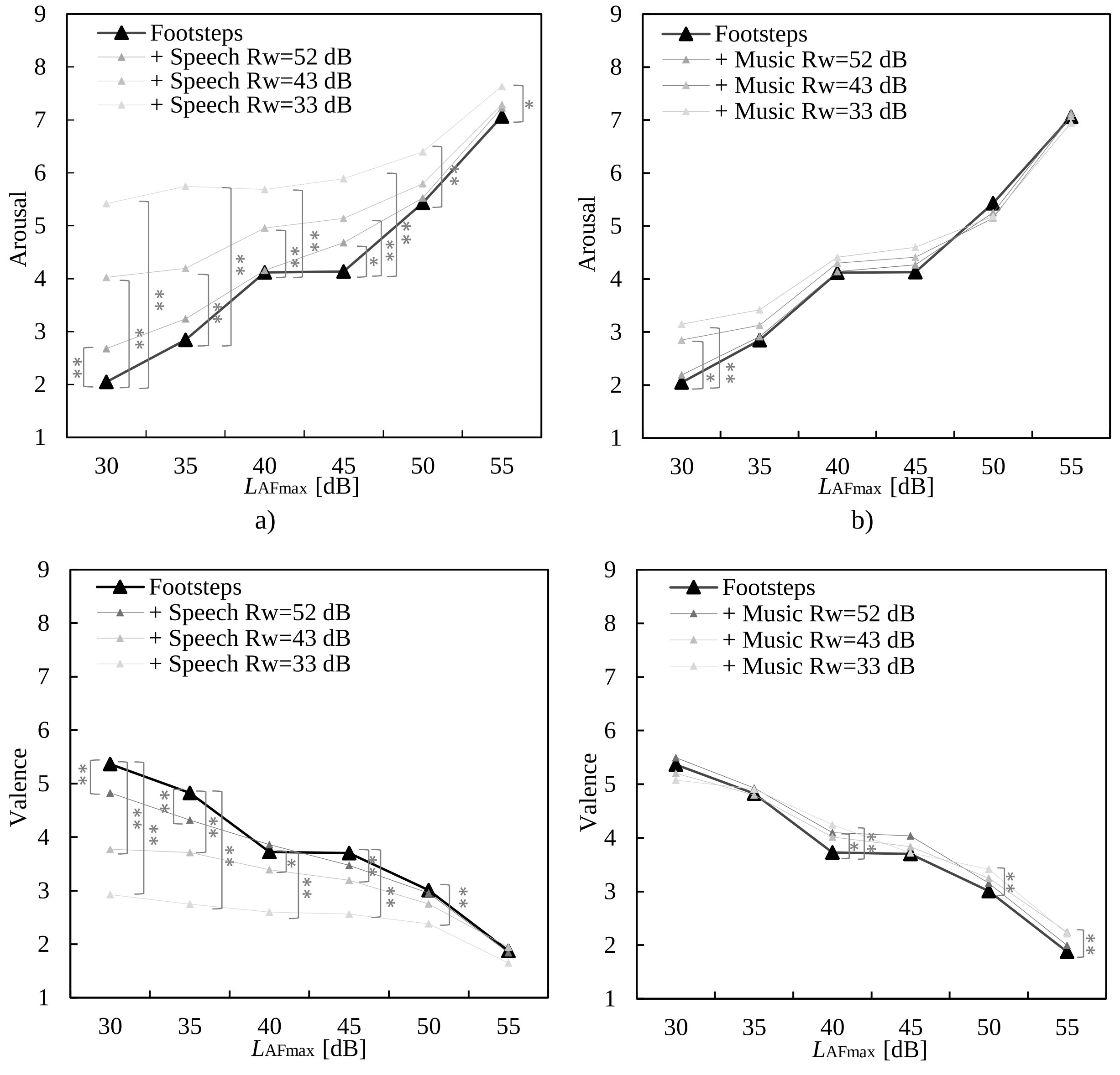


○ ○ ○ ○ ○ ○ ○ ○ ○


Training Session 5min
Session I: Single sound sources 17 min
Session II: Combined sound sources 21 min
Session III: Combined sound sources 21 min
Session IV: Combined sound sources 21 min
Break
Break
Break
End
One stimulus presentation
Baseline 10 s
Sound stimulus 20 s
Questionnaire 10 s


Appetitive motivation
Defensive motivation
Adult walking
Child running
Speech
Music
Valence
Arousal
1
2
3
4
5
6
7
8
9
Appetitive motivation
Defensive motivation
Footsteps and speech
Footsteps and music
Valence
Arousal

a) b)

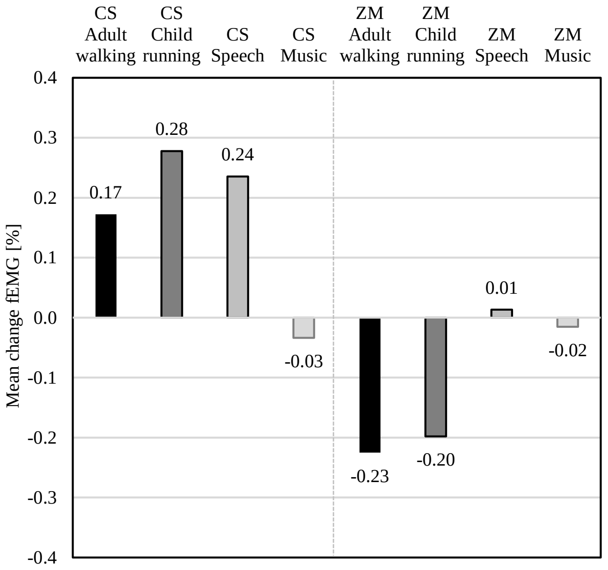

Footsteps
+ Speech Rw=52 dB
+ Speech Rw=43 dB
+ Speech Rw=33 dB
Arousal
Valence
+ Music Rw=52 dB
+ Music Rw=43 dB
+ Music Rw=33 dB
L_{AFmax} [dB]
1
2
3
4
5
6
7
8
9
30
35
40
45
50
55
*
**

a)

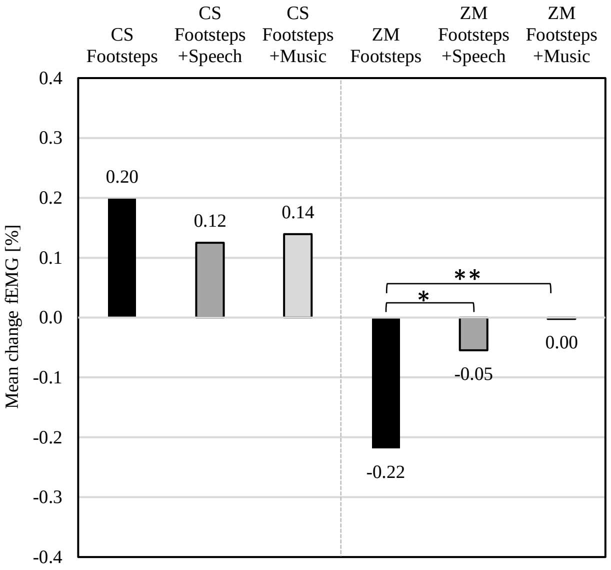
b)

c)

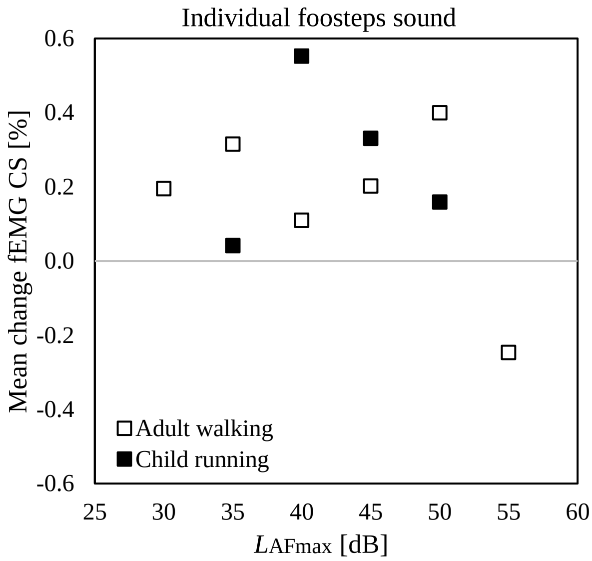
d)


CS Adult walking
CS Child running
CS Speech
CS Music
ZM Adult walking
ZM Child running
ZM Speech
ZM Music
Mean change fEMG [%]
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0.17
0.28
0.24
-0.03
-0.23
-0.20
0.01
-0.02

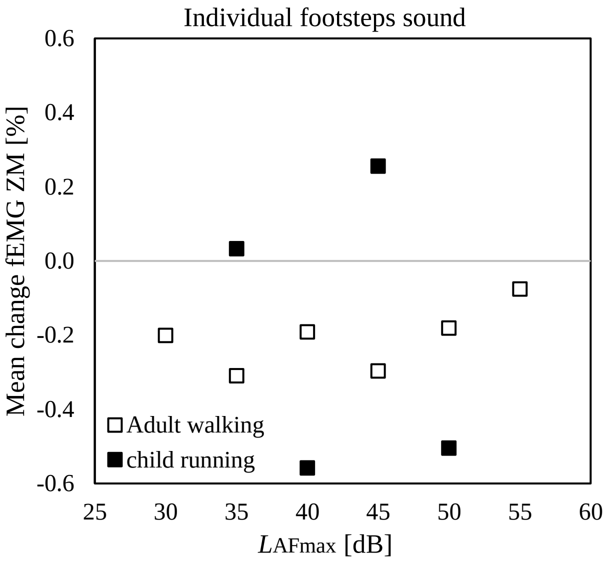
a)


CS Footsteps
CS Footsteps +Speech
CS Footsteps +Music
ZM Footsteps
ZM Footsteps +Speech
ZM Footsteps +Music
Mean change fEMG [%]
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0.20
0.12
0.14
-0.22
-0.05
0.00
*
**

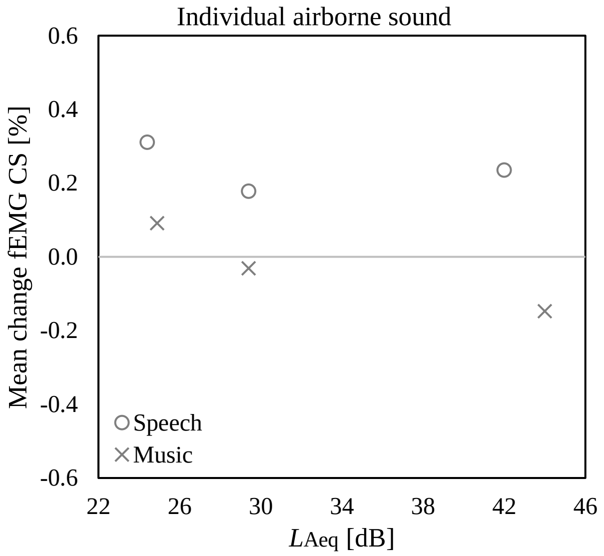
b)


Individual foosteps sound
Mean change fEMG CS [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
□ Adult walking
■ Child running
25
30
35
40
45
50
55
60
LAFmax [dB]

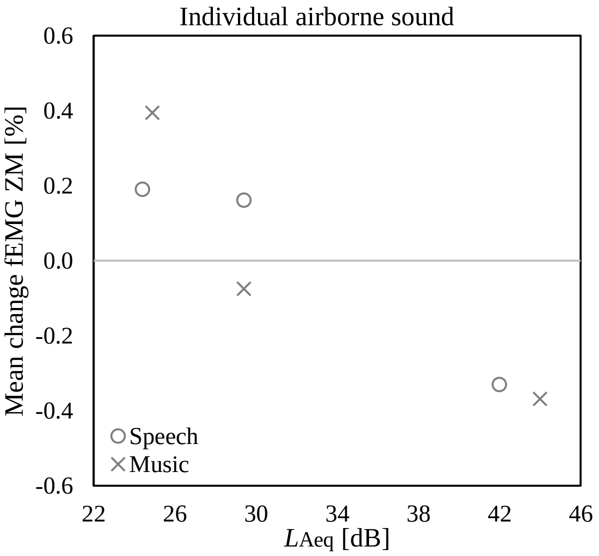
a)


Individual footsteps sound
Mean change fEMG ZM [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
□ Adult walking
■ child running
25
30
35
40
45
50
55
60
LAFmax [dB]

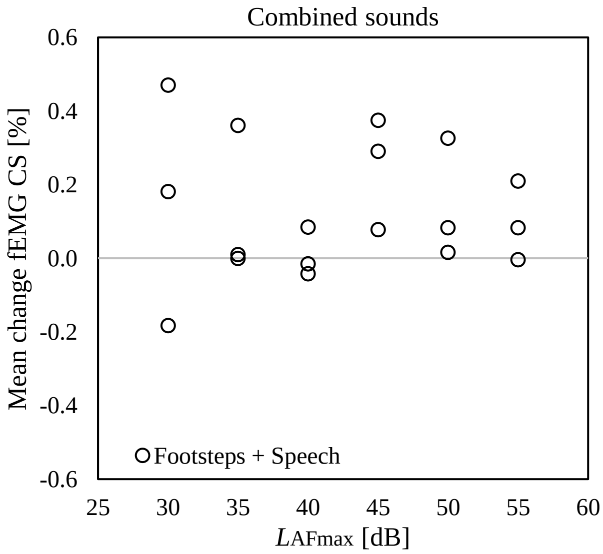
b)


Individual airborne sound
Mean change fEMG CS [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
○ Speech
× Music
22
26
30
34
38
42
46
LAeq [dB]

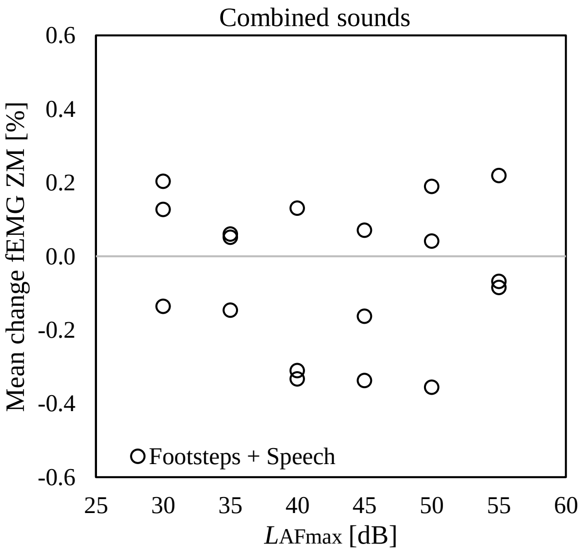
c)


Individual airborne sound
Mean change fEMG ZM [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
○ Speech
× Music
22
26
30
34
38
42
46
LAeq [dB]

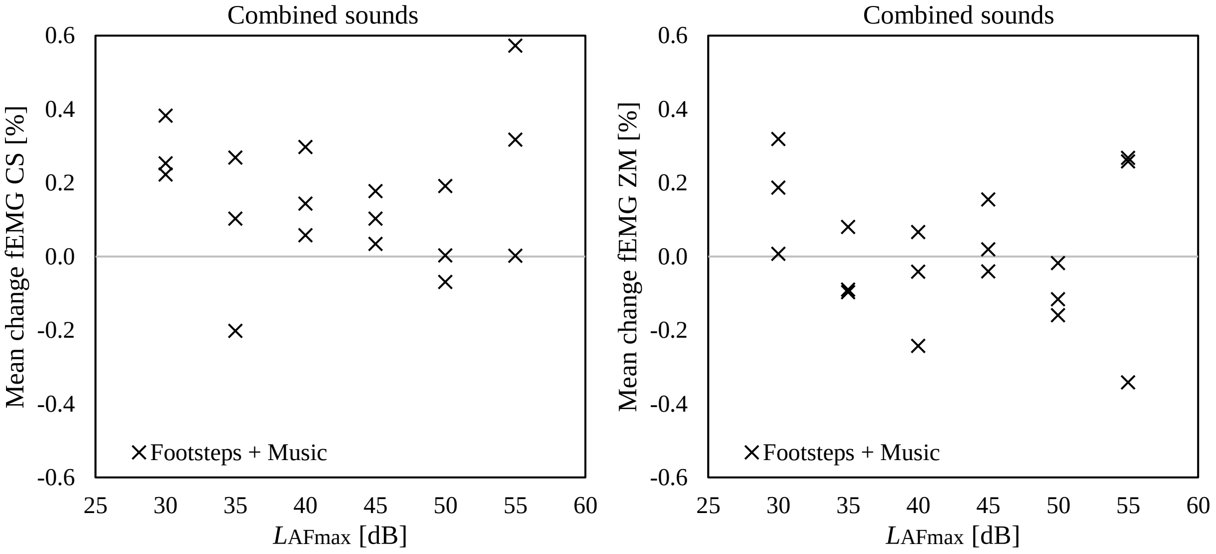
d)


Combined sounds
Mean change fEMG CS [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
○ Footsteps + Speech
25
30
35
40
45
50
55
60
LAFmax [dB]

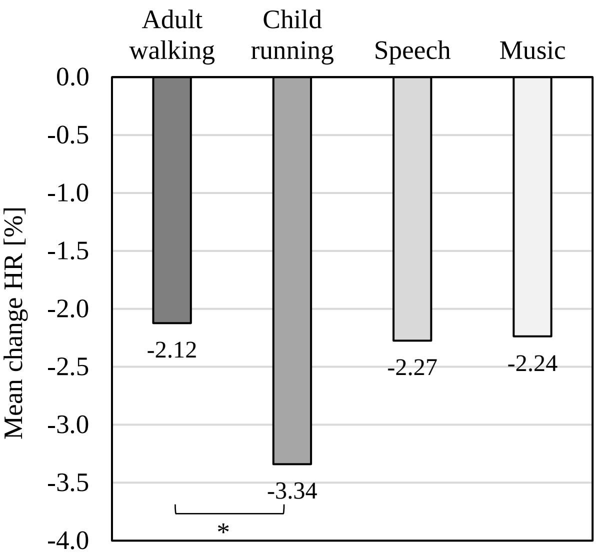
e)


Combined sounds
Mean change fEMG ZM [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
○ Footsteps + Speech
25
30
35
40
45
50
55
60
LAFmax [dB]

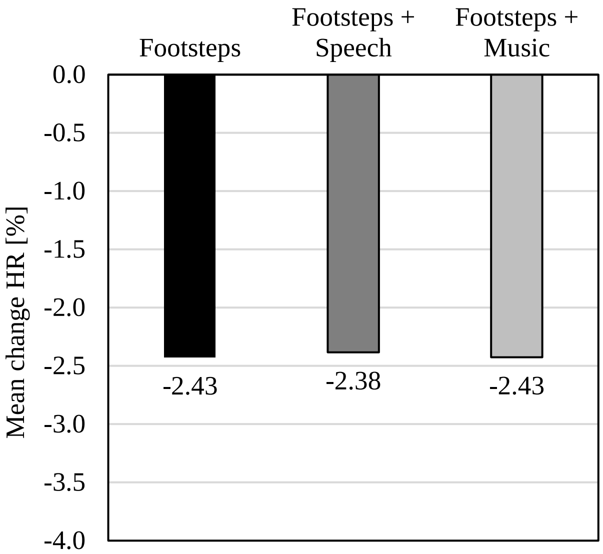
f)


Combined sounds
Mean change fEMG CS [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
25
30
35
40
45
50
55
60
LAFmax [dB]
× Footsteps + Music
Combined sounds
Mean change fEMG ZM [%]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
25
30
35
40
45
50
55
60
LAFmax [dB]
× Footsteps + Music

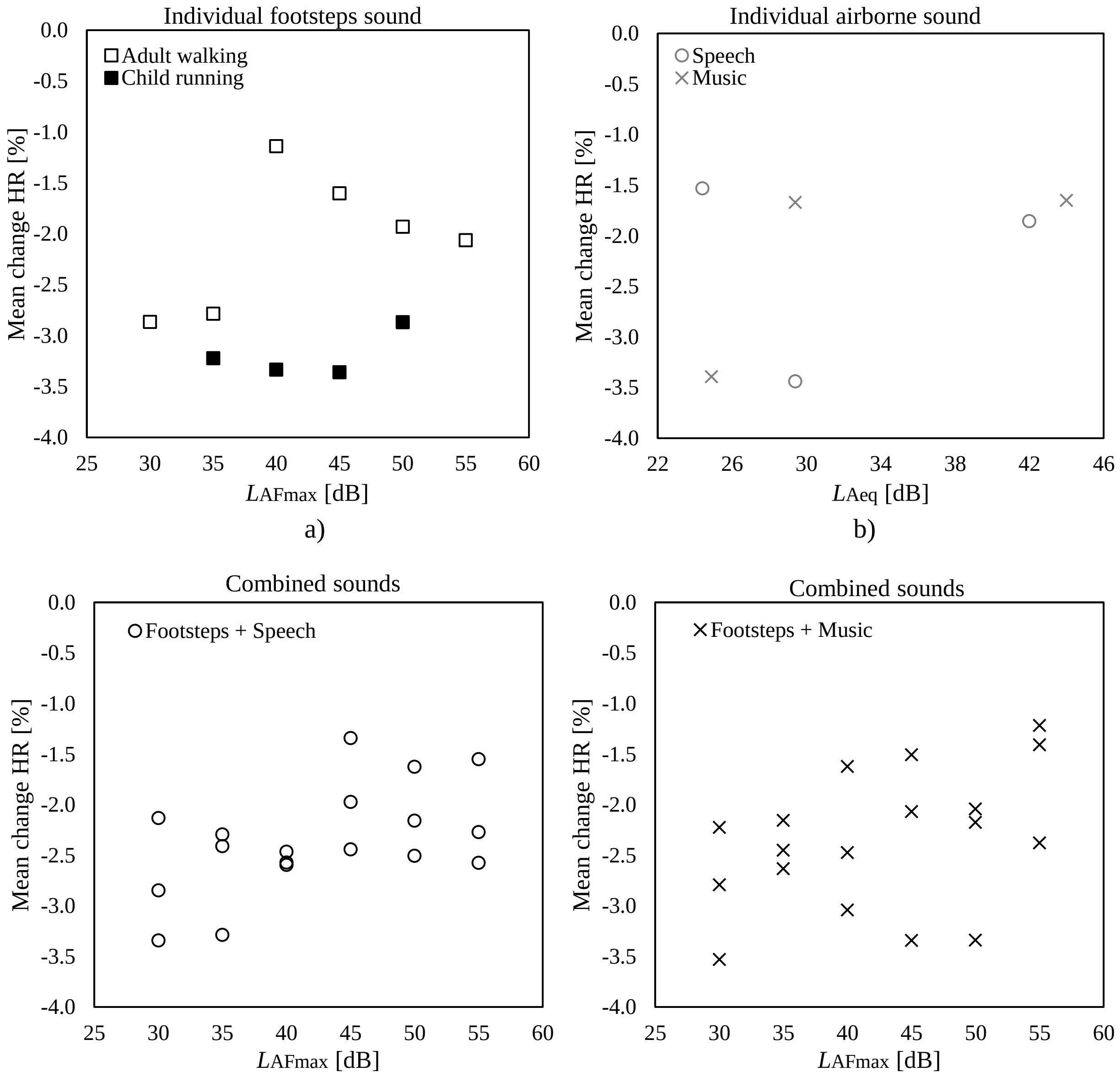
g) h)


Adult walking
Child running
Speech
Music
Mean change HR [%]
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-2.12
-3.34
-2.27
-2.24
*

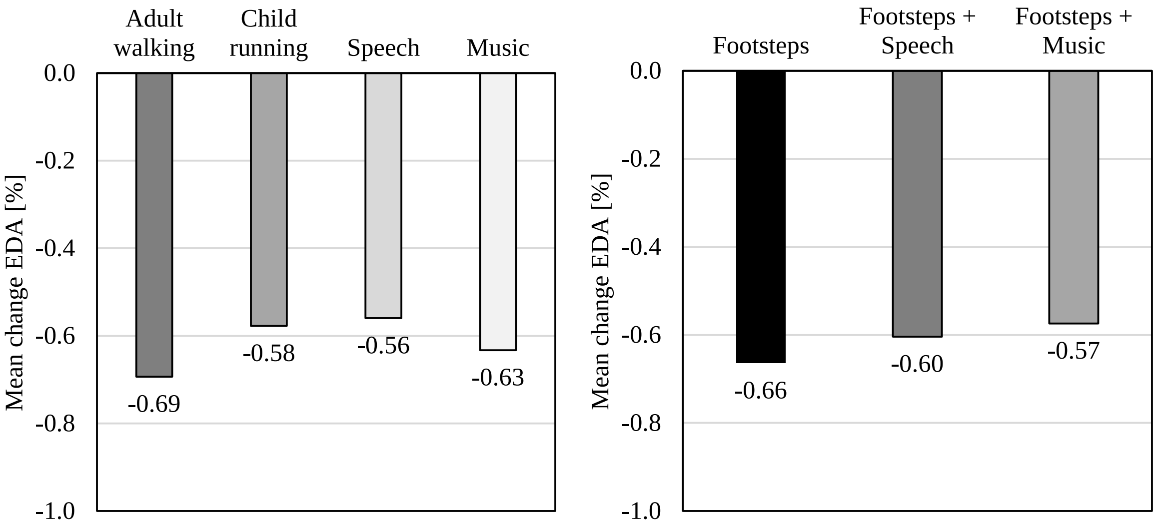
a)


Footsteps
Footsteps + Speech
Footsteps + Music
Mean change HR [%]
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-2.43
-2.38
-2.43

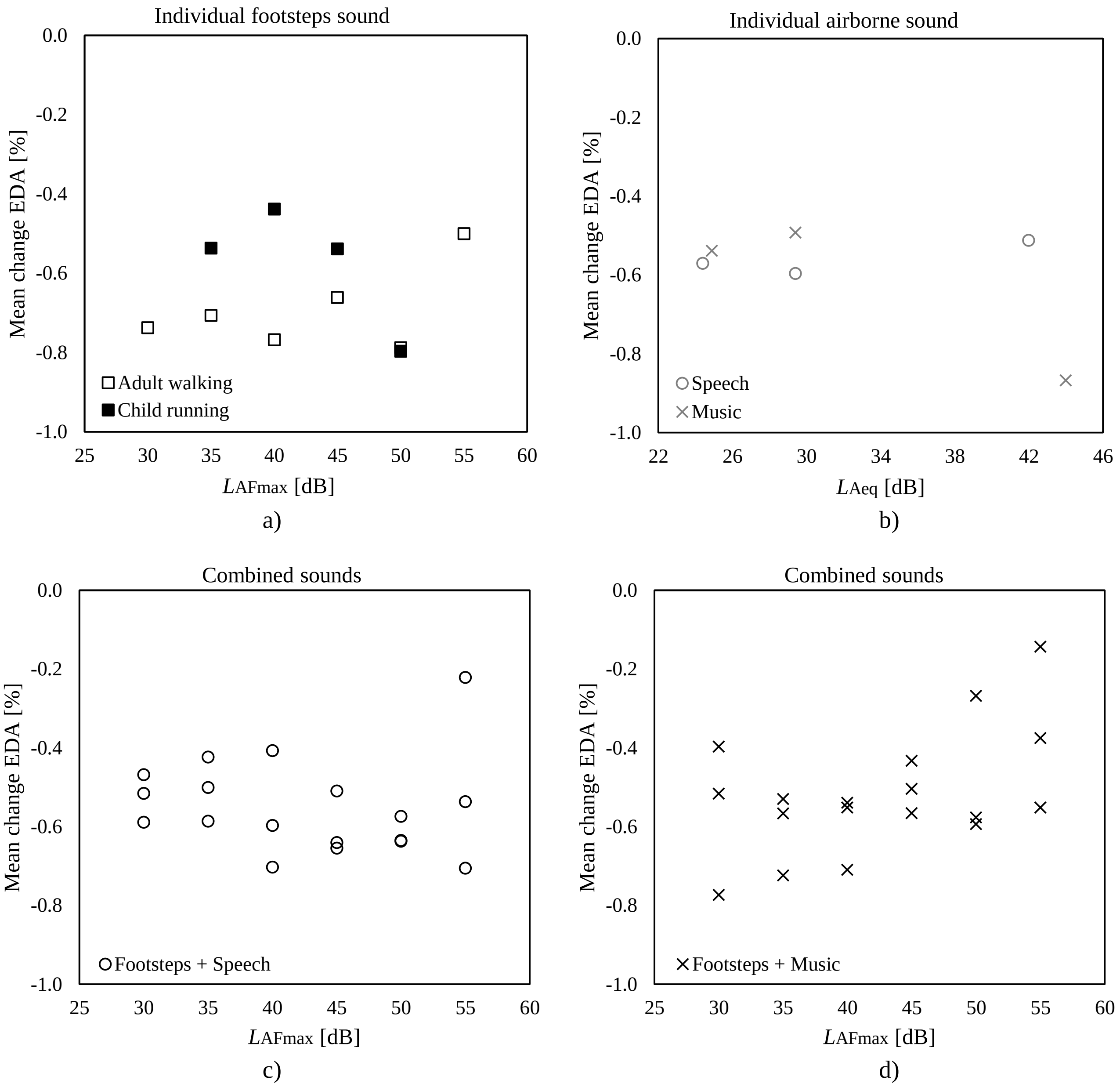
b)

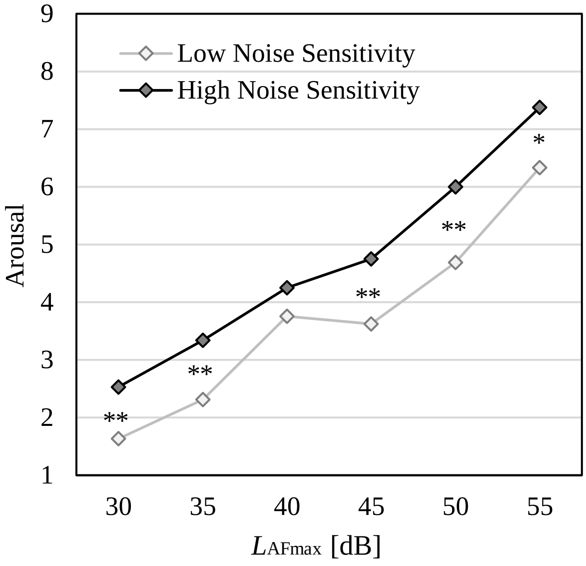
Individual footsteps sound
Adult walking
Child running
Mean change HR [%]
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
25
30
35
40
45
50
55
60
LAFmax [dB]
Individual airborne sound
Speech
Music
Mean change HR [%]
22
26
30
34
38
42
46
LAeq [dB]
Combined sounds
Footsteps + Speech
Mean change HR [%]
LAFmax [dB]
Combined sounds
Footsteps + Music
Mean change HR [%]
LAFmax [dB]

a) b) c) d)

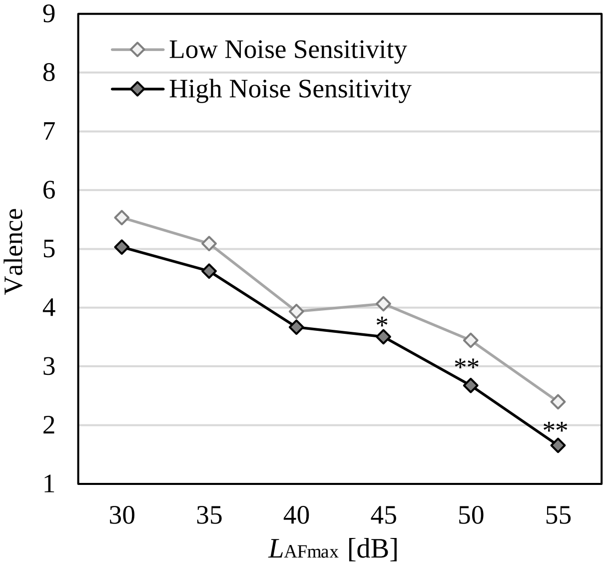

Adult walking
Child running
Speech
Music
Mean change EDA [%]
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-0.69
-0.58
-0.56
-0.63
Footsteps
Footsteps + Speech
Footsteps + Music
Mean change EDA [%]
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-0.66
-0.60
-0.57

a) b)


Individual footsteps sound
Mean change EDA [%]
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
25
30
35
40
45
50
55
60
LAFmax [dB]
Adult walking
Child running
a)
Individual airborne sound
Mean change EDA [%]
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
22
26
30
34
38
42
46
LAeq [dB]
Speech
Music
b)
Combined sounds
Mean change EDA [%]
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
25
30
35
40
45
50
55
60
LAFmax [dB]
Footsteps + Speech
c)
Combined sounds
Mean change EDA [%]
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
25
30
35
40
45
50
55
60
LAFmax [dB]
Footsteps + Music
d)


Low Noise Sensitivity
High Noise Sensitivity
Arousal
9
8
7
6
5
4
3
2
1
30
35
40
45
50
55
L_{AFmax} [dB]
**
**
**
**
*

a)


Low Noise Sensitivity
High Noise Sensitivity
Valence
9
8
7
6
5
4
3
2
1
30
35
40
45
50
55
L_{AFmax} [dB]
*
**
**

b)