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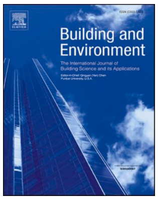

EEG alpha wave responses to sounds from neighbours in high-rise wood residential buildings

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ABSTRACT

This study explored electroencephalogram (EEG) alpha waves (α-EEG) in response to neighbours' sounds in wood residential buildings. Experiments were carried out in a laboratory to collect α-EEG data in distinct acoustics scenarios. A series of impact and airborne sounds were generated using loudspeakers and subwoofers, while the participants sat comfortably in a simulated living room wearing EEG headsets. Impact sounds were those of footsteps of adults walking on floors equipped with different timber floor configurations, whereas airborne sounds were of speech and music digitally filtered to resemble the good and poor sound insulation performances of lightweight vertical partitions. The sound sources were presented both individually and in combination (e.g. footsteps combined with music or speech). Noise sensitivity and attitudes towards neighbours were introduced as non-acoustic factors. The study highlighted significantly higher α-EEG in response to footsteps heard through floors characterised by low impact sound pressure levels (SPL) and to music heard through partition walls with low sound reduction indices. The effective duration of the autocorrelation function, τ_e, was computed to investigate subjective preference, and significant differences between sounds heard at various SPLs were identified for speech and music. Footsteps sounds in combination with an airborne source elicited higher α-EEG when compared to single footsteps sounds. Participants with self-reported low noise-sensitivity and positive attitude towards neighbours showed significantly larger α-EEG responses when exposed to sounds from neighbours than those who had high noise-sensitivity and negative attitude towards neighbours.

1. Introduction

Sound from neighbours is a common occurrence in contemporary densifying cities, where the construction of high-rise lightweight buildings is promoted as environmentally sustainable. However, high-rise wood buildings often fail to ensure acoustic comfort, and their residents are typically exposed to various sounds from neighbouring units, including impact and airborne ones [1–3]. As the presence or absence of sound at home prompts visceral reactions that interact with residents' daily lives in meaningful ways, neighbours' sounds may significantly reduce their quality of life [4,5]. Owing to their unpredictable nature and high information content, sounds from neighbours (e.g. speech, music, and footsteps) have also been shown to have a relatively high annoyance potential compared to other sound sources [6]. Previous studies have found that neighbours' sounds are a major source of annoyance and emotional responses in an urban environment and that exposure to these sounds can strongly influence physical and mental health [6–8]. For instance, the Danish Health and Morbidity Surveys stated that people living in multi-storey housing reported significantly higher neighbour noise annoyance than traffic noise annoyance (35.6% and 21.6%, respectively) and that annoyance provoked by neighbours noise was strongly associated with not getting enough sleep to feel rested [9]. Moreover, hearing sounds from neighbours attracts greater attention than sounds produced by visible sound sources, as they are acousmatic in nature, and residents do not have direct visual access to the sound source [10]. This effect can be accentuated when residents relax in their homes as low-intensity activities make people more sensitive to the acoustic environment, especially when the sound is generated by other humans [11]. The growth in the number of occupants teleworking from their homes in recent years also worsens the problem as, in addition to an increase in the time spent at home and consequently of noise exposure, remote work introduces disturbance as an additional effect of neighbours' noise exposure in multi-unit residential buildings [12,13].

Concerns about sounds from neighbours are exacerbated by the growing interest in wood lightweight structures, which are rapidly spreading around the world due to their proclaimed high environmental sustainability [14,15]. However, the acoustic environment in these new residential spaces, framed by lightweight timber partitions with limited sound insulations, may cause acoustic discomfort and noise annoyance for the residents [16]. Poor impact sound insulation of lightweight floor structures poses particularly a problem, as footsteps sound is one of the

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most commonly heard sounds in residential buildings and causes complaints in several countries [17–21]. For instance, in a Finnish survey conducted in 1998–99, when resident were asked how living in a timber apartment was different form living in a traditional heavyweight construction, one of the most common responses was poor impact sound insulation of footsteps [22]. This is consistent with the findings of the same survey repeated in 2017, which showed that impact sounds from the apartment unit above were one of the main sources of disturbance. In a study on acoustic comfort in timber building conducted in Sweden [3], it was also found that impact noise from neighbours perceived through floors caused the biggest annoyance. Although not pronounced as for impact sound, airborne sound transmission can be an issue in lightweight structures, resulting in annoyance and activity disturbance [16]. This effect can be accentuated in densely populated apartments blocks, where residents share spaces horizontally and vertically, and are simultaneously exposed to impact sounds from upstairs and airborne sounds from adjacent units [23].

Various approaches have been adopted to explore reactions to neighbours' sounds in residential contexts. For instance, Park et al. [24] interviewed residents of multi-storey housing. Meanwhile, questionnaire surveys [7,9,25,26] were conducted to collect community responses to sounds from neighbours, whereas laboratory experiments were conducted to identify the effects of acoustic and non-acoustic factors on psychological responses (e.g. annoyance) [27–31]. Laboratory experiments have also been conducted to identify various aspects of the subjective evaluation of neighbour sounds (e.g. emotions and physiological responses) [27,32]. Previous studies [33,34] have identified significant changes in heart rate, electrodermal activity, movement of facial muscles, and respiration rates after exposure to sounds generated by footsteps, speech, and music from neighbouring units. However, physiological responses are regulated both by the peripheral nervous system and by the central nervous system [35]. In particular, brain activity has the potential to provide strong information regarding the mechanisms underlying the subjective evaluation of sounds. Electroencephalogram (EEG) sensors can be used to measure the brain activity in response to auditory stimuli, providing high temporal resolution directly from the scalp. With the development of portable and practical EEG devices, an increasing number of researchers have incorporated EEG into acoustic research [36–39].

Many studies have focussed on EEG alpha waves (α-EEG), which refers to EEG activity in the range 8–13 Hz. α-EEG has been shown to have good test reliability, high reproducibility, and can detect early stages of annoyance, subjective preference, and restoration [37,40–42]. For example, Paszkiel et al. [36] found that α-EEG significantly decreased during a stressful task and significantly increased after sound exposure, with an autonomous sensory meridian response triggering, whereas relaxing sounds evoked greater α-EEG response compared to silence or rap music. According to Ahn et al. [43], the sound generated by a singing bowl, a sound healing tool made primarily of bronze and tin, was also found to increase α-EEG. Koelstra et al. [37] identified a significant negative correlation between α-EEG and valence, while higher arousal was found to lead to a decrease in α-EEG when participants were exposed to music clips with various emotional contents. Choi et al. [44] exposed participants to multi-modal environments varying temperature, odours, and sound exposure. They found higher relative α-EEG for the less stressful environment in the frontal lobe and suggested that the relative α-EEG was useful in assessing environments for stress. Li et al. [45] conducted a soundscape study, highlighting better α-EEG response to natural sound compared to traffic noise, where no significant changes over time were observed. Li et al. [39] also measured the EEG response in nine locations during in-situ walks in mountainous parks, observing that α-EEG was consistently greater in only audio settings compared to audio-visual conditions. This suggests that natural sounds produced more restorative benefits than positive visual aspects. Chen et al. [38] recently explored the annoyance and EEG rhythms of passengers on high-speed trains and found that the relative power of α-EEG increased as annoyance increased. According to Asakura [35], α-EEG was highly correlated with the results of subjective evaluation after exposing participants to sounds from a burbling river and white noise. However, despite being a frequent key locus of contestation for residents of an urbanised environment, in previous research, there has been no attempt to investigate neighbour sounds using EEG responses.

Additional features can be extracted by α-EEG; for example, based on the autocorrelation function (ACF) parameters, researchers adopted the effective duration of the envelope of the normalised ACF of α-EEG, τ_e [46]. Several studies have highlighted that τ_e values of the ACF are significantly greater for a preferred stimulus than for a non-preferred stimulus [47–51]. Moreover, significant differences in the left hemisphere were identified for subjective preference of temporal features of sounds (e.g. reverberation time and initial time delay) [47,48], whereas significant differences in the right hemisphere were observed for subjective preference in spatial features (e.g. interaural cross correlation (IACC)) [52]. However, most approaches using τ_e mainly focused on symphonic music clips to investigate preference in room acoustics [47,48], whereas τ_e of EEG responses provoked by everyday sonic events, such as neighbour sounds, have not yet been analysed.

Not every resident hears the sounds in the same manner [53–55]. Sensory differences can be a major issue for some groups of people and have a significant impact on their health, social integration, financial security, and overall well-being [55]. For instance, people with aural divergent conditions, such as high sensitivity to noise, may be at risk of more severe effects from unwanted exposure to neighbours sounds. Data from several studies suggest that noise sensitivity significantly affects the perceived annoyance provoked by environmental and neighbours' sounds, with individuals who self-report high sensitivity to noise being more annoyed by the presence of unwanted sounds [56–59]. Attitude towards the noise source was also identified as a factor affecting responses to sounds in residential contexts [60–63]. In particular, Park and Lee [62] conducted in-depth interviews with residents of multi-storey housing and recognised how attitudinal factors in neighbour noise issues should be regarded differently from other environmental noises, as people can develop direct and interpersonal relationships with the noise source, that is, the neighbours who make the noise.

Despite being a very common issue, research on the effect of exposure to sounds from neighbours remains scarce and rarely includes the effect of personal traits when compared to other environmental sound sources (e.g. transportation, wind turbines, and industrial sites). With increasing demand for high-rise wood residential buildings, there is a need for better understanding of human responses to neighbours' sounds in these specific residential contexts. Therefore, this research set out to investigate α-EEG responses elicited by common sounds form neighbours as a first step towards understanding the effect of everyday sounds from neighbours in wood residential buildings on brain activity. A laboratory experiment was performed focusing on the effect of impact sounds caused by adults walking upstairs and airborne sounds generated from neighbouring units, including speech and music. The participants listened to a series of acoustic stimuli resembling neighbour sounds through various partitions while wearing an EEG monitoring system. It was first hypothesised that α-EEG might differ across sound sources heard through partitions characterised by different sound insulation performances. Accordingly, all sound stimuli were recorded and filtered to represent the different sound insulation performances of the horizontal and vertical partitions in lightweight buildings. The ACF parameter τ_e was introduced to further assess the preferred acoustic scenarios. Second, it was assumed that participants would exhibit different responses to different types of sound sources (e.g. impact or airborne sounds and single or combined sounds). Finally, it was conjectured that participants with different sensitivities to noise and different attitudes towards neighbours would exhibit different α-EEG in response to the same sounds from neighbours.

2. Methodology

2.1. Participants

The participants were recruited after the study was approved by the Central Ethics Committee of the University of Liverpool (Reference number: 8006; approval on 20 October 2020). Thirty adults (19 males and 11 females, with self-reported normal hearing) participated in the experiment after being recruited through study advertisements at the Fire Insurers Laboratories of Korea (FILK) and local universities. Their ages varied between 20 and 49 years (median: 40, std: 8.6). Except for a few participants living in detached or terraced houses, the majority (22 out of 30) lived in apartments. Before the experiment, the participants were asked to answer several questions regarding their noise sensitivity and attitudes towards their neighbours.

Noise sensitivity was evaluated using a 12-item questionnaire, NoiSeQ-R [64], and an additional question: 'I am sensitive to noise'. Overall, noise sensitivity scores varied between 2 and 37 ($\sigma = 6.6$). Based on their overall scores, the participants were divided into high and low noise sensitivity groups and those in the moderate range were excluded. First, the participants' NoiSeQ-R overall scores were divided into five groups using the 20th, 40th, 60th, and 80th percentiles from the observed mean score distributions as the cutoff points. Second, the middle range between the 40th and 60th percentiles was excluded. Thus, the 11 participants who scored below the 40th percentile were classified as the 'low noise-sensitivity group' (Mdn = 42.3, $\sigma = 6.6$), whereas the 12 participants who scored above the 60th percentile were classified as the 'high noise-sensitivity group' (Mdn = 41.2, $\sigma = 9.0$).

Attitudes towards neighbours were evaluated using a translated five-item questionnaire based on quotes from a previous study [62]. The English and Korean questionnaires are presented in Table A1. The overall score on this questionnaire served as a reference to identify the degree to which participants had a favourable (i.e. positive) or unfavourable (i.e. negative) attitude towards their neighbours. Similar to the noise sensitivity grouping, the 12 participants who scored below the 40th percentile were classified as the 'negative attitude towards neighbours group' (Mdn = 37.4, $\sigma = 8.1$), whereas the 12 participants who scored above the 60th percentile were classified as the 'positive attitude towards neighbours group' (Mdn = 44.5, $\sigma = 7.7$).

2.2. Sound stimuli

The sound stimuli used in this study were impact sounds from upstairs and airborne sounds from adjacent units. Impact sounds were recorded in a laboratory, while airborne sounds were anechoic recordings [65]. The laboratory consisted of two vertically adjacent rooms separated by a customizable floor sample. On the top floor (source room), an adult walked on the floor sample, while sounds were recorded in the receiving room beneath. Sound absorbing panels were placed in the receiving room to simulate the typical reverberation time in furnished living rooms (approximately 0.5 s). Fig. 1 shows the sound recordings in the laboratory. The footsteps sounds were recordings of an adult walking on two timber floor structures: 1) a basic structure composed of a timber joist slab with a chipboard panel on top and 2) the same structure equipped with a floating floor and suspended ceiling. Carpet tiles were installed on both the structures to represent common floor finishes in residential buildings. The airborne sources included a lively conversation ('speech') and a piece of classical piano music ('music'). The sound stimuli were manipulated to represent the worst and best floors and walls in terms of sound insulation performance. The SPLs (L_{AFmax}) of adults walking range within 27–56 dB in four different floor configurations [65]; therefore, adult walking sounds of 30 dB and 50 dB were chosen from the floor structures ($L_{n,w} = 37$ dB and 76 dB). Airborne sounds were digitally filtered using Adobe Audition to simulate lightweight partitions with different sound insulation levels. The weighted sound reduction indices (R_w) of the two simulated partitions were 52 and 33 dB, respectively. For the partition with $R_w = 52$ dB, the SPLs (L_{Aeq}) of speech and music were 24 and 25 dB, respectively. Similarly, for poor partitions with $R_w = 33$ dB, the levels were 42 and 44 dB for speech and music respectively. The frequency characteristics of the sound stimuli are shown in Fig. 2.

2.3. Experimental design

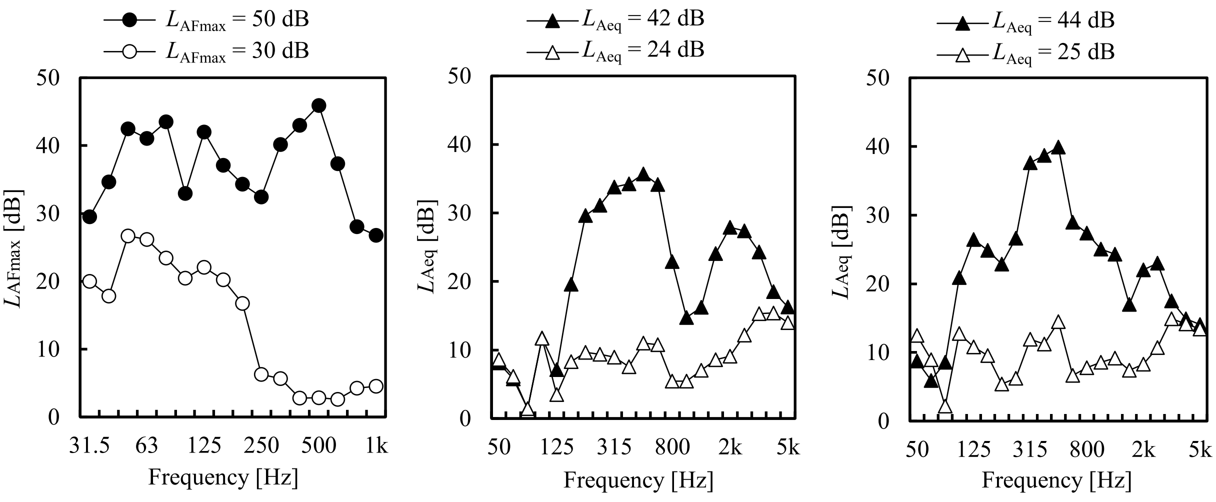
The laboratory experiment was conducted in a soundproof room with a low background noise level (~25 dB, L_{Aeq}) at the FILK. The room had a floor area of approximately 35.7 m^2 (4.8 m × 7.4 m), simulating a living room in a typical apartment. The participants were seated on a sofa and wore an EEG headset, while the sound stimuli were presented through loudspeakers (GENELEC – 8030A) placed 2 m in front of them (for airborne sound sources) and 1.5 m above them (for impact sounds). Additionally, a subwoofer (GENELEC-7060B) was placed in front of the participants to deliver low-frequency sounds below 63 Hz. White noise (NC 25) was presented as ambient noise through a loudspeaker (GENELEC-8050A) placed in front of the participants in the simulated living room.

2.4. EEG response acquisition

The B-Alert X24 wireless EEG system (Advanced Brain Monitoring, Carlsbad, CA, USA) was used for EEG data acquisition. The EEG responses were recorded throughout the experiment including the resting periods. In accordance with the International 10–20 system [66], the following 20 EEG channels shown in Fig. 3 were acquired: Fp1, Fp2 (prefrontal lobe), F3, F4, Fz, F5, and F6 (frontal lobe); T3, T4, T5, and T6 (temporal lobe); C3, Cz, and C4 (central lobe); P3, Pz, and P4 (parietal lobe); and Poz, O1, and O2 (occipital lobe). The data were collected at a sampling rate of 256 Hz with the following bandpass characteristics: a 0.1 Hz high-pass filter and a 100 Hz fifth-order low-pass filter. To avoid artefacts related to eye movements and blinks, the participants were

a) b)

Fig. 1. Impact sound recordings in the laboratory: a) an adult walking on the floor sample in the source room, and b) the receiving room equipped with microphones and sound absorbing panels.



a) b) c)

Fig. 2. Frequency characteristics of sound stimuli: a) footsteps, b) speech, and c) music.

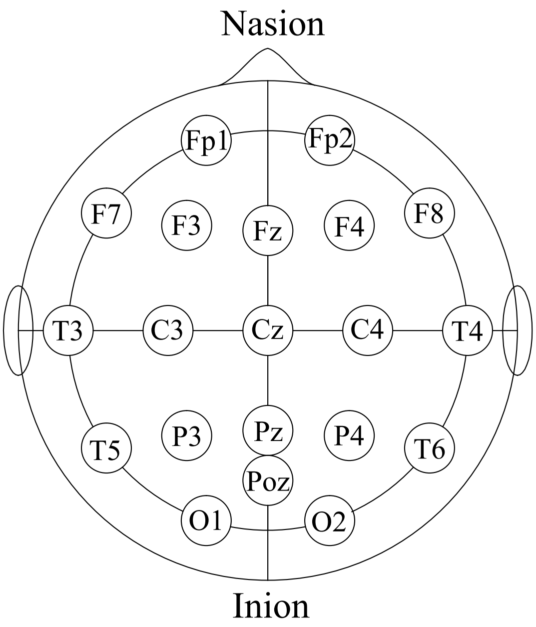


Fig. 3. Anatomical sensor distribution of the multi-channel EEG system: prefrontal (Fp), frontal (F), central (C), parietal (P), temporal (T) and occipital (O) areas with the indication of nasion and inion point.

asked to keep their eyes closed during the stimuli presentation. Data from B-Alert® X24 were monitored through STAT software (03.08.03.00 version). Using a MATLAB R2017a code, the recorded EEG data were digitally bandpass filtered using Butterworth filters with cut-off frequencies at 8 and 13 Hz for isolating α-EEG. Running α-EEG and root-mean-squares of each epoch were then computed. Among the full recordings, the responses during the baselines and noise exposures were analysed. In addition, τ_e of α-EEG were computed to obtain a degree of similar repetitive features of the continuous brain waves [52]. For τ_e, the ten-percentile delay (i.e. −10 dB) was determined by fitting the straight-line regression for the initial −5 dB day rate of the ACF envelope [46].

2.5. *Procedure*

Prior to participation, the participants were provided with a participant information sheet and written consent form. After obtaining consent, the participants were asked to sit on a couch wearing an EEG headset. The experiment consisted of two combined sound sessions and one single sound session, as annoyance caused by single and combined sounds were different [23]. The single-sound session lasted 7 min, whereas the remaining sessions, with presentations of impact sounds combined with airborne noise sources lasted 8 min. All sound sources and sessions were randomised across participants to avoid order effects. A baseline was maintained for 10 s before each noise stimulus, and each sound stimulus was then presented for 20 s. A 10 s resting period was given before the next stimulus. It was assumed that participants' reactions to noise would be most critical while they were relaxing. During the experiment, participants were asked to imagine being relaxed in their own homes, while sounds came from neighbouring units.

2.6. *Data analysis*

EEG responses were analysed using a MATLAB R2017a code, developed for the extraction of α-EEG power, α-EEG running power and τ_e. Statistical analyses were performed using SPSS for Windows version 26 (SPSS Inc. Chicago, IL). Independent samples *t*-tests were conducted to estimate the significance of the difference in α-EEG between 1) the first and second parts of each stimulus, 2) sound sources heard through floors and walls with different sound insulation performances and 3) τ_e in the left and right hemispheres. Analysis of variance (ANOVA) was used to investigate the effect of sound source type on α-EEG. The data of the groups from different non-acoustic factors were not normally distributed. Thus, a nonparametric test (Kruskal-Wallis test) was carried out to examine the differences in α-EEG responses between individuals with self-reported low and high noise sensitivity, and between participants with a self-reported positive or negative attitude towards neighbours. Gardner-Altman plots were used to quantify effect sizes and assess the precision of the statistical analyses [67]. In the figures, the top section reports all individual measurements as a swarmplot to display the underlying distribution. The effect size is reported in the bottom section, with the mean difference between the groups depicted as a black dot and 95% bootstrap confidence intervals calculated from nonparametric sampling of the collected data, shown by the shaded curve and whiskers.

3. Results

3.1. Effect of different partitions on α-EEG to single sounds

Firstly, the influence of different horizontal and vertical partitions on the α-EEG responses to neighbours sounds was investigated. Fig. 4 shows the averaged running α-EEG in the prefrontal, frontal, temporal, central, and parietal lobes of the scalp over the 20 s period of the stimulus presentation. The occipital lobe was excluded from the analysis because it is typically associated with visual stimulus responses [42]. Overall, the running α-EEG tended to increase in all the monitored lobes over time. This tendency was more significant for the two airborne sound sources (speech and music) than for the impact sound (footsteps). The magnitudes of the running α-EEG in the different lobes were similar across the three different sound sources. For instance, α-EEG was the highest in the prefrontal lobe (~0.7 log μV), followed by the frontal, central and parietal lobe (0.58–0.68 log μV), whereas the lowest values were acquired for the temporal lobe (~0.5 log μV). During the first half of stimulus presentation, suppression of the α-EEG was observed, as the α-EEG for the first 10 s was lower than that for the remaining period (10–20 s). Differences between the first and latter parts were confirmed using *t*-tests ($p < 0.01$) for all the sounds. Additionally, the effects of the SPLs on the α-EEG were clearer during the first 10 s. Thus, it was decided to use the averaged α-EEG for the first 10 s in the following part of the analysis.

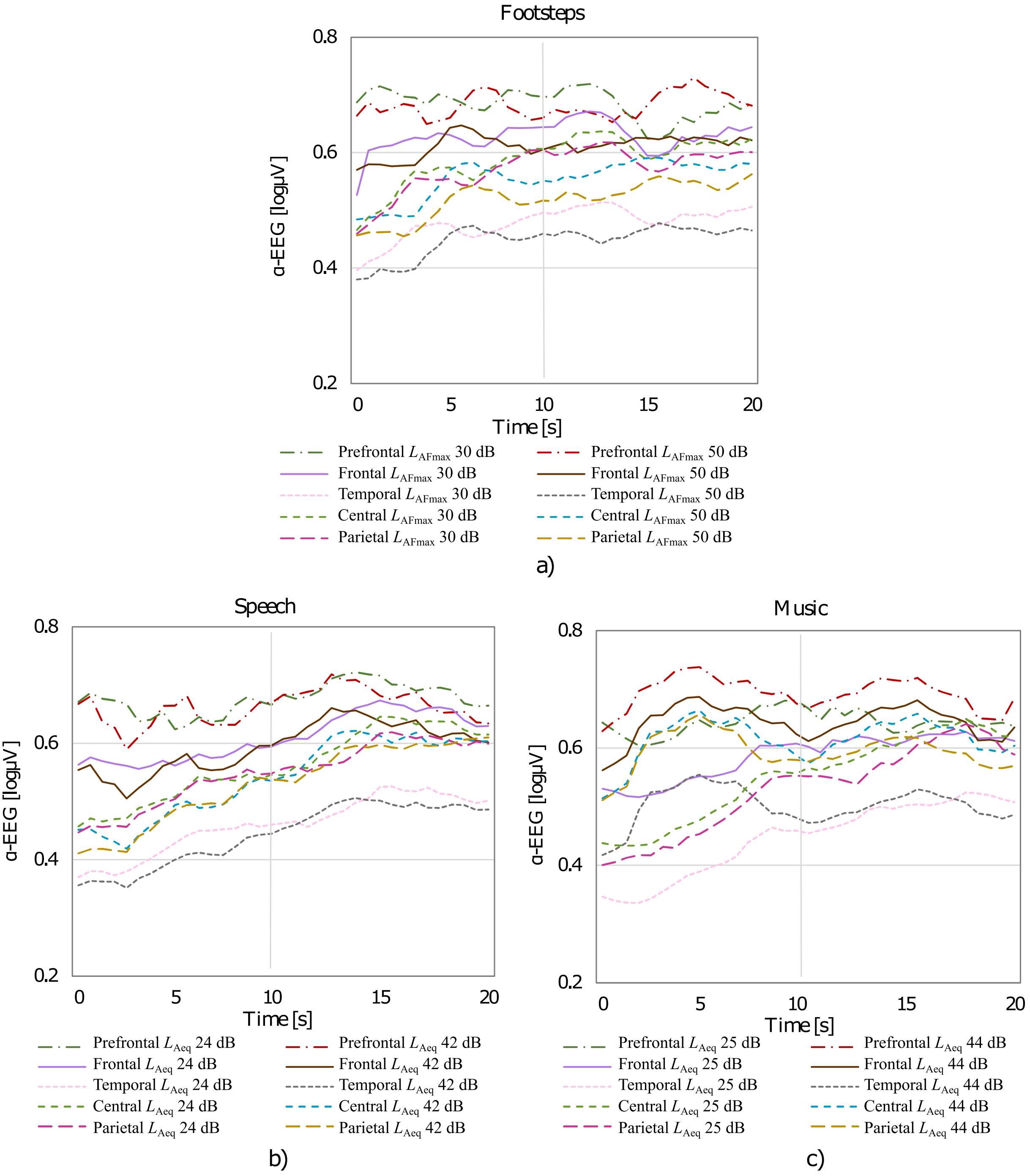


Fig. 4. Running α-EEG during the presentation of a) footsteps, b) speech, and c) music sounds at different SPLs and in different lobes.

The mean differences in α-EEGs for footsteps, speech, and music heard through different partitions are plotted in the Gardner-Altman plots of Fig. 5. Overall, the footsteps and speech sounds were quite different from those of the music clips. For instance, footsteps sound from the floor assembly with good sound insulation performance at 30 dB (L_{AFmax}) elicited higher α-EEG than the other at 50 dB, characterised by poor sound insulation performances. Similarly, the speech clip with lower SPL (L_{Aeq} = 24 dB) elicited higher α-EEG that the other with greater SPL (L_{Aeq} = 42 dB). Conversely, for music clips, higher α-EEG was measured from the partition wall with poor sound insulation performance and greater SPL (i.e. R_w = 33 dB, resulting in L_{Aeq} = 44 dB). Subsequently, the *t*-tests were conducted to the individuate significance of the differences in α-EEG between the sound clips through different partitions. For footstep and speech sounds, no significant differences were found in the overall or lobe-specific responses. Unlike the footsteps and speech sounds, the music clips showed significant differences in both overall α-EEG ($p < 0.01$) and for every single lobe ($p < 0.05$ for temporal and parietal lobes, $p < 0.01$ for prefrontal, frontal, and central lobes).

3.2. *Effect of different partitions on* τ_e

For the overall values, the value of τ_e was averaged separately for left and right hemispheres because the hemispheres are affected by different attributes of sounds. For example, spatial impressions are registered by the right hemisphere [52], whereas attributes that vary in the time domain mainly affect the left hemisphere [47,49]. Fig. 6 represents the overall τ_e values across the sources, hemispheres and SPLs. For footsteps and speech sounds, lower SPLs led to longer τ_e in both hemispheres, whereas the music clips with greater SPL showed longer τ_e. For footsteps sounds (Fig. 6a), τ_e of the sounds at two SPLs were similar and the differences were not significant in both the hemispheres (left: $p = 0.266$ and right: $p = 0.464$). However, the difference was significant for speech and music clips ($p < 0.01$ for both the left and right hemispheres) (Fig. 6b and 6c). In particular, the music clips exhibited greater differences between the two SPLs in both the hemispheres. The differences in τ_e between the two music clips were 278 and 319 ms in the left and right hemispheres, respectively. These differences were much larger than those between the two speech clips (83 ms and 74 ms for the left and right hemispheres, respectively).

Similar patterns were observed from the results in each lobe for the two hemispheres. The differences in τ_e between footsteps sounds at different SPLs were not significant in all the lobes. In contrast, for speech, significant differences were found in every lobe except for the left parietal ($p < 0.01$ for prefrontal, frontal, temporal and central lobe; $p < 0.05$ for right parietal), whereas there were several significant differences for music ($p < 0.05$ for right prefrontal; $p < 0.01$ for frontal, temporal, and central lobe). It was also observed that τ_e values from both the hemispheres were similar for all the sound sources except for speech sounds in the parietal lobe and the music clips in the prefrontal lobe.

3.3. *Effects of sound sources on α-EEG*

Additional analyses were performed to examine the effects of different types of single sources (footsteps, speech, and music) and to compare single sources with combined sound sources (i.e. footsteps combined with speech or music). In the following analyses, the α-EEG results were averaged across the SPLs. As shown in Fig. 7, the differences in α-EEG across the sound sources were minor in all the lobes. Fig. 7a represents the running α-EEG for single sound sources in the left (T3 and T5) and right (T4 and T6) temporal lobes which are typically associated with the responses to auditory stimuli [68]. Similar to the results in Fig. 4, α-EEG for single sound sources increase with time. However, music clips showed remarkably different patterns between footsteps and speech, with a significant increase at the beginning of sound exposure. The result of ANOVA revealed that the type of single sources had a significant effect on the overall α-EEG [F (2,2157) = 3.177, $p < 0.05$]. A *post-hoc* test confirmed that there was a significant difference between speech and music ($p < 0.05$). The sounds from acoustically good (footsteps at 30 dB, speech at 24 dB, and music at 25 dB) and bad partitions (footsteps at 50 dB, speech at 42 dB, and music at 44 dB) were analysed separately. For the sounds at lower SPLs, the effect of the type of source on α-EEG was not significant [F (2,1797) = 2.193, $p = 0.112$], whereas, for the sounds at higher SPLs, the effect of the type of source became significant [F (2,1797) = 20.368, $p < 0.01$]. *Post-hoc* tests confirmed that the music clip elicited significantly greater α-EEG than footsteps or speech ($p < 0.05$ for both lower and greater SPLs).

Subsequently, the analyses were extended to α-EEG in response to single footsteps sounds and combined sounds. Fig. 7b and 7c show the running α-EEG in the temporal lobe for footsteps heard singularly (in black) or in combination with speech or music (in grey). The combined sound sources showed higher α-EEG than single sounds. The ANOVA results revealed that significant differences between the sound sources were found in the overall α-EEG [F (2,5080) = 8.208, $p < 0.01$] and the temporal lobe [F (2,1492) = 3.149, $p < 0.05$]. For the overall responses, *post-hoc* tests confirmed that the difference between footsteps and footsteps combined with speech was significant ($p < 0.05$). However, this was not the case for footsteps and footsteps with music ($p = 0.968$). Another significant difference was identified between the combined sources (footsteps + speech and footsteps + music, $p < 0.01$). For the temporal lobes, *post-hoc* tests also confirmed a significant difference between footsteps combined with speech or music ($p < 0.05$).

3.4. *Effect of non-acoustic factors on α-EEG*

The effect of non-acoustic factors on α-EEG in response to neighbours' sounds was analysed by comparing the participants with different noise sensitivity and attitude towards neighbours. Fig. 8a shows the overall α-EEG from low or high noise-sensitivity groups for single sounds. Participants with low noise-sensitivity showed greater α-EEG than those are sensitive to noise. The same results were obtained for all specific lobes for all the sound sources. Kruskal-Willis tests showed that the differences in overall α-EEG were significant for all the sound sources ($p < 0.01$ for footsteps and speech, $p < 0.05$ for music). The differences were also significant in every specific lobe (i.e. prefrontal, frontal, temporal, central, and parietal) for footsteps and speech sounds ($p < 0.01$), whereas significant differences were found in the prefrontal, frontal, and central lobes for music ($p < 0.01$ for prefrontal and frontal, $p < 0.05$ for central lobes). The α-EEG of participants with a positive or negative attitude towards neighbours is shown in Fig. 8b. In general, participants with a positive attitude towards neighbours showed greater α-EEG than those with negative attitude towards their neighbours for all the sound sources. Kruskal-Willis tests confirmed that the differences between the groups were significant ($p < 0.05$, footsteps and speech; $p < 0.01$ for music). Unlike noise sensitivity, a few significant differences were identified in specific lobes, such as the frontal and temporal lobes for speech and music ($p < 0.01$), and the parietal lobe for speech ($p < 0.05$).

4. Discussions

4.1. *Effect of different partitions and sound sources on α-EEG*

This investigation found that the overall α-EEG responses differ significantly when single footsteps and music sounds from neighbours are heard through different horizontal and vertical partitions. For instance, higher α-EEG was associated with footsteps sounds through the timber floor characterised by good sound insulation performance ($L_{n,w}$ = 37 dB) compared to footsteps heard through the horizontal partition with low sound insulation performance ($L_{n,w}$ = 76 dB). Conversely, listening to music clips at 42 dB showed greater α-EEG than the same sound filtered through a partition wall characterised by good sound

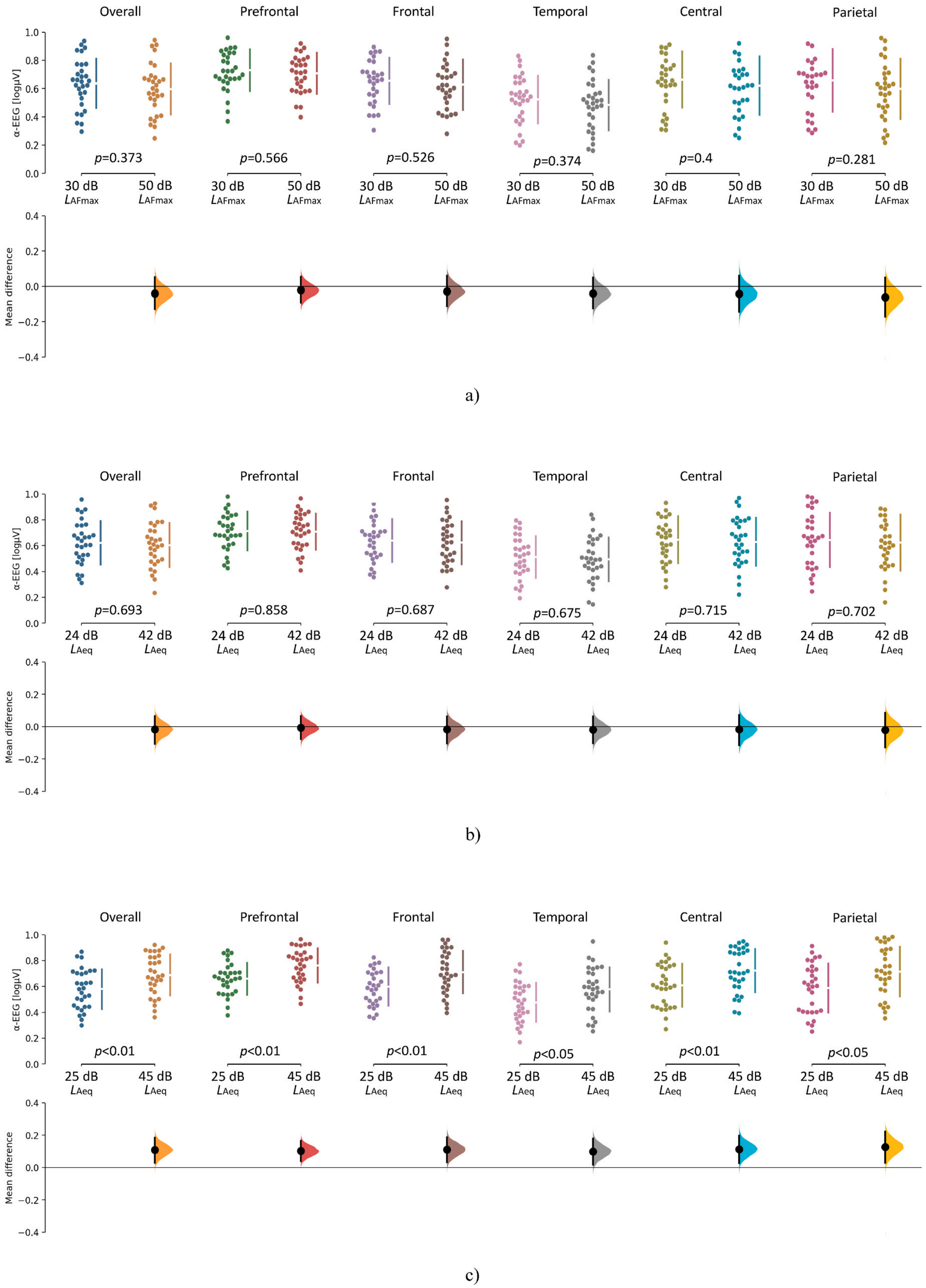


Fig. 5. Mean difference for comparisons of overall and lobe-specific α-EEG for a) footsteps, b) speech, and c) music heard through different partitions. The raw data are plotted on the upper axes; each mean difference is plotted on the lower axes as a bootstrap sampling distribution. Mean differences are depicted as dots, and 95% confidence intervals are indicated by the ends of the vertical error bars.

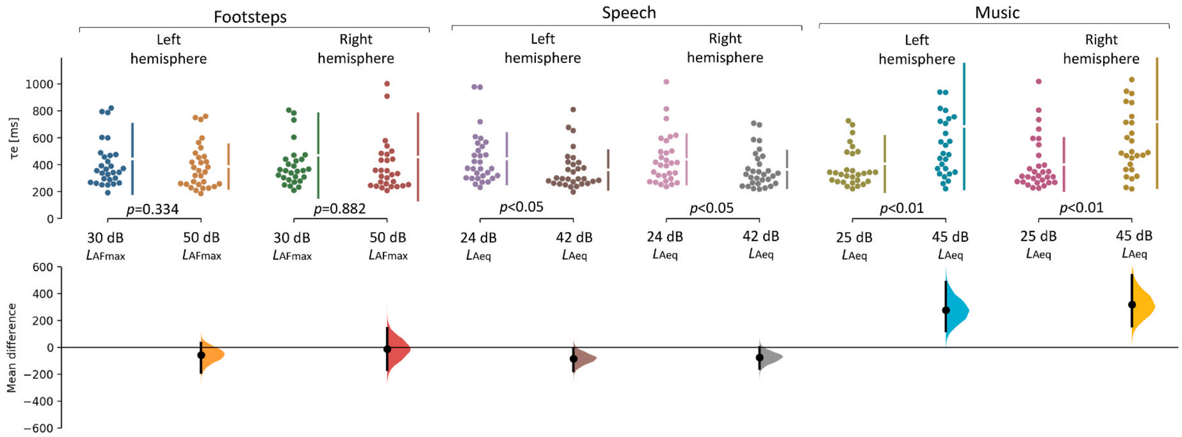


Fig. 6. Comparison of τ_e and the mean difference in response to footsteps, speech, and music heard through different partitions. The upper axes report raw data; each mean difference is plotted on the lower axes as a bootstrap sampling distribution. Mean differences are depicted as dots; 95% confidence intervals are indicated by the ends of the vertical error bars.

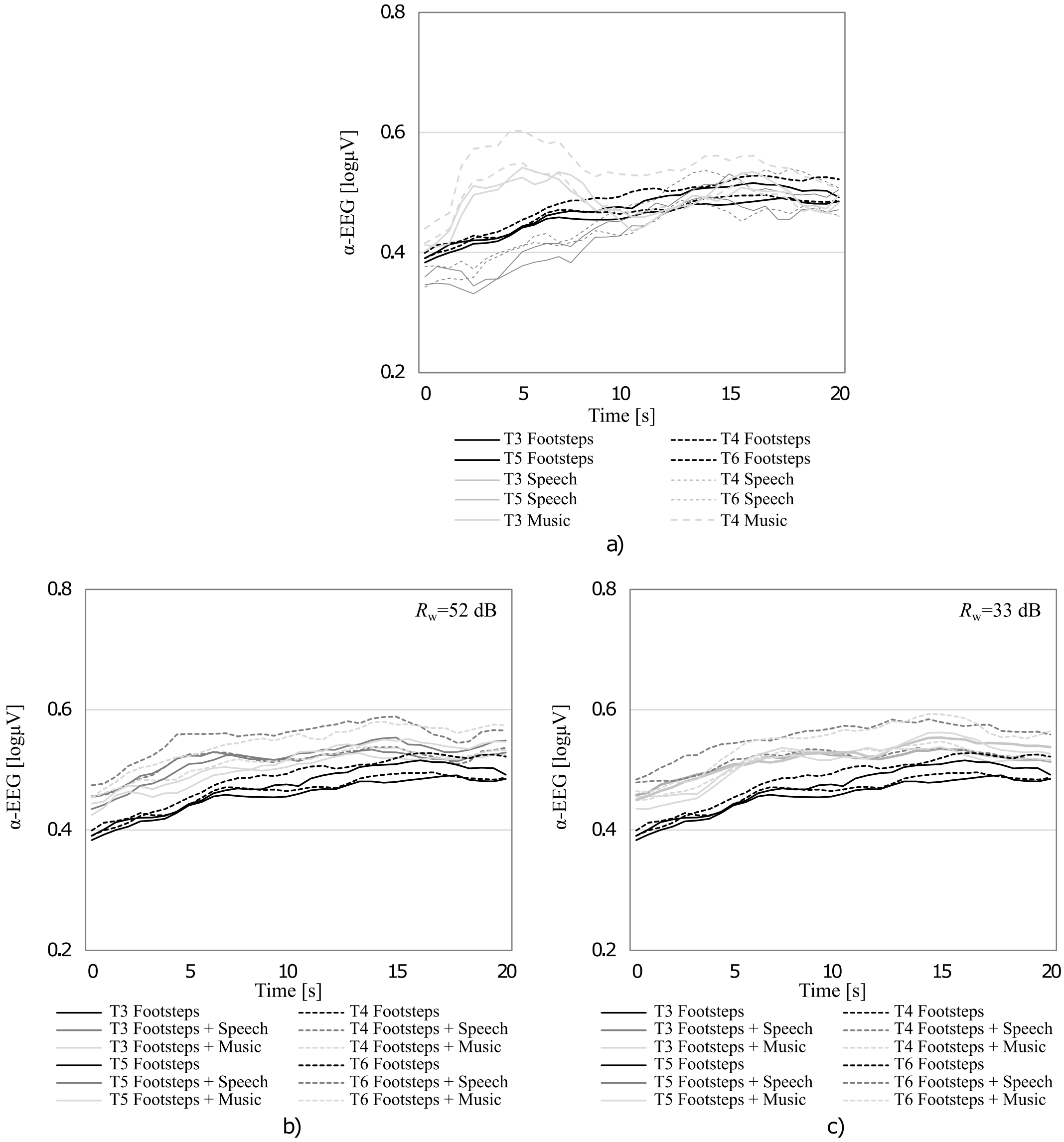


Fig. 7. α-EEG in the temporal lobe in response to a) different single sounds (footsteps, speech, and music), b) single and combined sounds through vertical partition with R_w = 52 dB, and c) single and combined sounds through vertical partition with R_w = 33 dB.

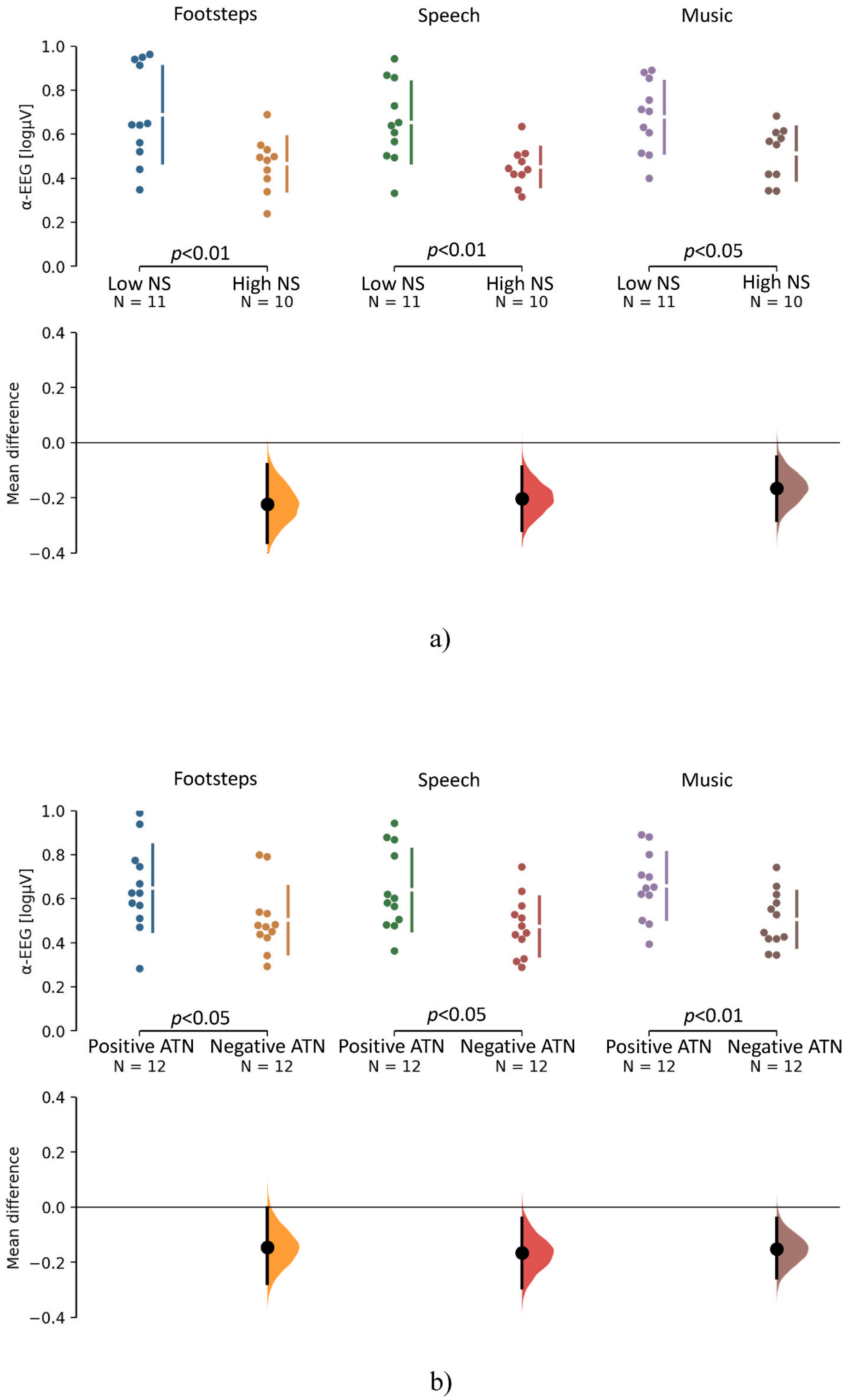


Fig. 8. Comparison of overall α-EEG in response to single sounds across the participants with different a) noise sensitivity (NS) and b) attitude towards neighbours (ATN). The upper axes report raw data; each mean difference is plotted on the lower axes as a bootstrap sampling distribution. Mean differences are depicted as dots and 95% confidence intervals are indicated by the ends of the vertical error bars.

insulation performance ($L_{\mathrm{Aeq}} = 24$ dB). As higher α-EEG is typically associated with subjective preference [37,42], these findings suggest that a lower SPL of footsteps sound and a higher SPL of music are preferred in indoor residential spaces. In particular, the classical music piece, which was assumed to be from neighbours, showed larger α-EEG at a higher SPL because the sound was due to low arousal music and was relaxing, which possibly led to stress reduction [69]. However, different results can be expected for other music clips of different genres and preferences. For instance, Paszkiel et al. [36] reported that classical music led to a larger α-EEG response than rap music, indicating that α-EEG is affected by the type of music. Similarly, Koelstra et al. [37] reported a significant correlation between low-arousal and pleasant music videos and an increase in α-EEG waves. On the other hand, the SPLs of the speech sounds (conversation) from partitions with good or poor sound insulation performances did not elicit significant differences in α-EEG. This might be attributed to stimulation of attentiveness than relaxation in listeners, where engagement is not usually reflected in alpha band brain activity [68]. This study revealed that the α-EEG differs across the types and characteristics of the airborne sound sources; thus, further studies with greater diversity in airborne sounds are required to draw a definite conclusion.

The effect of different types of sources (i.e. footsteps, speech, music, and footsteps combined with speech or music) on α-EEG was also investigated. The findings suggest that significant differences exist in the α-EEG elicited by speech and music, in which music elicited significantly higher α-EEG than speech. However, no significant differences were observed between the responses to impact (i.e. footsteps) and airborne (i.e. speech and music) sound sources. This is not consistent with previous research highlighting that EEG responses to speech and music were stronger and more time-locked (i.e. they manifested the same pattern at roughly the same time in each trial after stimulus onset) than others, including impact sounds [70]. However, sounds from the previous study were ‘non-human’ mechanical impact sounds, whereas the current experiment used human footsteps sounds. Thus, EEG responses to mechanical and human impact sounds may differ because people tend to be more sensitive to sounds generated by other humans [11] in a residential setting.

This investigation also suggests that the effect of the source type on EEG is mediated by the SPLs of the sources. For instance, when sound insulation performances of horizontal and vertical partitions were high (i.e. $L_{n,w} = 37$ dB and $R_w = 52$ dB), no significant differences in α-EEG were observed across the source types. Conversely, when the neighbours sounds were heard through partitions with poor sound insulation performances (i.e. $L_{n,w} = 76$ dB and $R_w = 33$ dB), the differences in α-EEG became significant between music and footsteps or speech sounds. Therefore, only sound stimuli above certain SPLs have a significant effect on α-EEG across various sound sources. For example, in this study, it was revealed that SPLs above 40 dB were required to achieve significant differences in α-EEG and confirmed previous findings on peripheral physiological responses such as heart rate and respiration rate [33]. This was slightly lower than the SPLs of the sound stimuli presented in soundscape studies [39,45,71] which reported significant changes in EEG responses in outdoor environments.

The overall α-EEGs in response to combined sound sources were significantly greater than those to single footsteps sounds in the current experiment. This suggests that footsteps sounds in combination are preferred to single footsteps sounds owing to additional airborne sounds. This is in accordance with a previous study [72] in which the peripheral physiological responses to the same sound sources used in this study were measured and in which facial electromyography in the zygomaticus major muscle group and respiration rate showed significantly less deactivation and deceleration during exposure to combined footsteps sounds than to single sounds. However, footsteps sounds combined with speech or music were found to be more annoying than single footsteps sound [23]. This disagreement may be attributed to lack of direct correlation between physiological and psychological responses [73]. For instance, attention to sounds may have affected the physiological responses. Specifically, α-EEG can be greatly diminished or totally eliminated by sudden alertness and mental concentration [74]. From a psychological perspective, listeners were more focused on floor impact sounds; thus, the sound sources heard in combination were more annoying. Conversely, from a physiological perspective, speech and music may have had positive effects on listeners at an unconscious level. However, Chen et al. [38] reported that α-EEG increased with increased psychoacoustics annoyance although there is still no clear consensus on the correlation between annoyance and EEG response. Furthermore, several researchers have suggested various EEG indices, which combine EEG sub-bands (i.e. α, β, γ, θ) to explain annoyance using EEG responses [38,75,76]. Accordingly, further research is required to determine the correlations among preference, annoyance and EEG responses.

4.2. Effect of different partitions and sound sources on τ_e

The τ_e has been widely used to identify preferred acoustic conditions, with regard to both spatial and temporal feature of sounds [42,47,49,51,52]. When extracted from α-EEG, the value of τ_e signifies the degree to which an α-EEG exhibits similar repetitive features in the time domain. Hence, longer τ_e of α-EEG indicates that the brain is repeating a similar rhythm under these preferred conditions. Accordingly, it was argued that the τ_e value of α-EEG was longer when the participant was presented with preferred conditions [51]. The findings of the current experiment confirm previous research [23] as a longer τ_e was observed when participants were exposed to footsteps and speech sounds with lower SPLs. For music clips, sounds with greater SPL resulted in longer τ_e values because they were considered more pleasant than footsteps or speech sounds in a previous study [72].

In general, significant differences in τ_e of α-EEG in the right hemisphere are linked to preference in spatial features of sounds (e.g. IACC) [52], whereas significant differences in the left hemisphere are associated with preference in temporal features (e.g. reverberation time) [47,49]. The focus of this study was on the variation in SPLs which is a temporal feature of sounds. Thus, it was assumed that the SPL would evoke the significant changes in τ_e in the left hemisphere. However, similar trends were observed in the two hemispheres for all sound sources, except in two cases (speech in the parietal lobes and music clips in the prefrontal lobes). This implied that the spatial features of the sound sources changed when the loudness of the front loudspeaker varied. However, the spatial characteristics of the sounds (e.g. IACC) were not analysed in this study; thus, further analysis of IACF parameters is required to understand the effect of temporal and spatial features on α-EEG in typical sounds of residential contexts.

The change in τ_e of the music clips at different SPLs was much greater than those of the speech and footsteps sounds at different SPLs. This might be because the participants were more familiar with footsteps sounds than with speech and music clips. Similarly, Walker [77] highlighted that greater α-EEG response was detected during exposure to less familiar music clips compared to more familiar pieces. These findings also confirm that τ_e is more sensitive to preferred sounds (e.g. music) than unpleasant sounds (e.g. footsteps). In addition, longer τe of α-EEG can reflect more activated and pleasant sound in the Russell's Circumplex model [78]. The τe can be helpful to find more activated and pleasant sounds in the noise control practice and acoustic design at home from physiological point of view.

4.3. Effect of non-acoustic factors on α-EEG

Similar acoustic scenarios may cause different responses in different people depending on several factors (e.g. activity at the time of exposure, attitude towards the source, participants' sensitivity to sounds, and controllability of the stressor) [79]. In this study, noise sensitivity significantly affected α-EEG responses. Individuals with low noise-sensitivity exhibited greater α-EEG than participants with high noise-sensitivity. This is consistent with a previous study [80] in which EEG responses to fMRI scanner noise were significantly lower for noise-sensitive participants than for those who were less sensitive to noise. In addition, this finding supports previous studies which found a significant effect of noise sensitivity on physiological responses. For instance, Stansfeld [81] identified higher electrodermal activity and heart rate acceleration in response to environmental noise in individuals with high noise-sensitivity. Meanwhile, according to Park et al. [58], people with high noise sensitivity showed greater electrodermal activity and decelerated heart rate than individuals with low noise sensitivity under exposure to floor impact noise.

However, the opposite finding was reported in a recent study that used footsteps, speech, and music sounds [72]. Frescura and Lee [72] reported that peripheral physiological responses (e.g. heart rate, facial electromyography, and electrodermal activity) were not significantly affected by the participants' noise sensitivity. A plausible reason for this may be that EEG measures the activity in the central nervous system, which provides a more direct response than peripheral somatic or visceral reactions. For instance, Hogervorst et al. [82] compared EEG, eye-related measures (i.e. pupil size and eye blink) and peripheral physiology measures (e.g. electrodermal activity, respiration, and electrocardiogram) to assess the mental workload. They found that EEG performed better than eye-related measures and peripheral physiology in terms of workload classification.

Attitude can affect EEG responses in diverse fields, such as politics [83] and branding [84]. In addition, Ogata [73] found that attitudes towards listening to different sound conditions differed significantly among many participants. Particularly in a domestic setting, Moch [85] suggested that the physical characteristics of noise are often less important than the resultant attitude towards the noise source. Consistently, this study also detected significantly different α-EEG responses among participants with a more, or less favourable attitude towards neighbours. Individuals with a positive attitude towards neighbours exhibited greater α-EEG in response to neighbours' sounds than participants with a negative attitude towards neighbours. This result is in agreement with the study by Park and Lee [62], who reported that attitudes towards neighbours led to different coping strategies and higher negative emotions in response to neighbour' sounds generated upstairs.

The results of the current study are also in good agreement with those of Jahncke et al. [86], who reported a significant correlation between the attitude towards the sound source and restoration likelihood. Previous investigations have highlighted how personality traits (e.g. temperament) significantly affect EEG responses during Zen meditation [87] and emotional imagination [88]. Accordingly, the role of personality traits can also be investigated in response to sounds from neighbours in residential contexts using EEG. For instance, Hagemann et al. [89] recently investigated how dispositional positive and negative effects can be predicted by resting EEG and suggested that greater tonic activation of the left temporal cortex increases susceptibility to experiencing negative emotions. Similarly, the lower α-EEG exhibited by participants with diverse attitudes towards neighbours could be mediated by their personality traits in future investigations.

4.4. Limitations and suggestions for further research

Most previous studies on EEG response during exposure to sound stimuli have dealt with environmental noise or soundscape [39,44,71]. Instead, in this study, sounds from neighbours were introduced by presenting hypothetical indoor residential acoustic scenarios, which might differ from previous studies. However, only a few sound stimuli have been selected from diverse types of neighbours sounds [19]. Thus, future research could expand the range of auditory stimuli, including sounds from domestic appliances (e.g. washing machines) and those from the outdoor environment. Additionally, presenting averaged α-EEG results could be reviewed in future analyses; this is because it was recently highlighted that biological responses to sound exposure may be affected by the impression of the sound, which varies among individuals [35]. Similarly, including questions on expectations and requirements regarding the acoustic environment, which varies across participants, may help in drawing meaningful interpretations of EEG responses in the context of exposure to everyday sounds.

The current study was limited by the absence of participants' activities during exposure to sounds from neighbours. For instance, various activities could be disturbed by noise while spending time in residential spaces [90]. Accordingly, future investigations can extend current methodology by monitoring the effect of neighbours sounds on EEG while participants engage in specific activities such as reading.

In the current investigation, suppression of running α-EEG was observed in the first half of the stimuli presentation (~10 s). This was not in accordance with previous research of Yokosawa et al. [91], which identified event-related suppression in MEG Tau rhythm (8–10 Hz), but not in α-EEG for the sounds (of duration 6 s) extracted from the IADS-2 with pleasant, neutral, and unpleasant emotional content. As only three different types of sound sources were adopted in the current experiment, the increase of α-EEG over time could be because the participants could predict the rest of the stimulus easily after 'recognising' the sound source in the first half (i.e. habituation effect). In future, this research can be extended to analyse frontal asymmetry in EEG responses to deepen the understanding of emotions owing to neighbouring sounds. According to previous investigations [92–94], the right frontal lobe is more reactive to unpleasant stimuli than is the left. Thus, a wider number of neighbours sounds with different affective states may lead to a range of frontal asymmetry in the EEG response.

5. Conclusions

This study aimed to observe the effect of neighbour sounds on EEG α-EEG waves, which identify subjective preference and states of relaxation. A listening test was conducted with impact (footsteps from upstairs) and airborne sounds (speech and music from siding units) heard through floors and partition walls, resembling poor and good sound insulation performance in lightweight wood buildings. Individual and footsteps sounds along with speech or music were presented to the participants while their brain activity was monitored. The effective duration of the ACF function extracted from α-EEG, τ_e, was also computed as a measure of repetitive features of α-EEG waves. Two non-acoustic factors (i.e. noise sensitivity and attitude towards neighbours) were introduced as mediators and were self-assessed using questionnaires before the experiment. The results indicate that α-EEG was affected by exposure to neighbours' sounds, and the SPL and type of sound source had a significant impact on the α-EEG response. For instance, footsteps sound through the floor performing good acoustically ($L_{n,w} = 37$ dB) elicited significantly higher α-EEG compared to footsteps heard through a floor performing poorly acoustically ($L_{n,w} = 76$ dB). Conversely, music heard through a partition wall characterised by a low sound reduction index ($R_w = 33$ dB) elicited greater α-EEG compared to the same clip heard through a wall characterised by a good sound reduction index ($R_w = 52$ dB). Significantly greater α-EEG was elicited in response to music, compared to footsteps or speech sounds. Additionally, hearing footsteps sound in combination with airborne sounds elicited greater α-EEG compared to single footsteps sound. Significant differences in τ_e were identified in both hemispheres during exposure to speech and music sounds varying in SPLs, but not during exposure to footsteps sound. This suggests that τ_e is a more appropriate parameter for the detection of preference rather than annoyance. Moreover, noise sensitivity and attitude towards neighbours significantly affected α-EEG during exposure to neighbours sounds. Participants with self-reported low noise sensitivity and positive attitude towards neighbours exhibited greater α-EEG compared to those with opposite traits.

CRediT authorship contribution statement

Alessia Frescura: Writing – original draft, Methodology, Investigation. **Pyoung-Jik Lee:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Jeong-Ho Jeong:** Resources, Data curation. **Yoshiharu Soeta:** Validation, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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