The Reaction of People on Low Frequency Noise and the Correlation with Measurement

Vom Fachbereich Elektrotechnik, Informationstechnik und
Medientechnik der Bergischen Universität at Wuppertal genehmigte
Dissertation

zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

von

M.Sc. Mu He

geboren am 28.01.1983 in Heilongjiang, China

Referent: Prof. Dr.-Ing. Detlef Krahé

Koreferent: Prof. Dr.-Ing. Jörg Becker-Schweitzer

Tag der Einreichung: 04.04.2016

Tag der mündlichen Prüfung: 24.06.2016

Die Dissertation kann wie folgt zitiert werden:

urn:nbn:de:hbz:468-20160728-084415-2
[http://nbn-resolving.de/urn/resolver.pl?urn=urn%3Anbn%3Ade%3Ahbz%3A468-20160728-084415-2]

Abstract

This thesis deals with the perception and reaction of people on low frequency noise (LFN) and the correlation with the objective and subjective measurements. LFN is a common noise type in the normal life, it has been studied a lot and researchers found physiological and psychological effects on people. There are many national standards and methods to measure and evaluate LFN, but the LFN complainants and problems are still increasing and many aspects about LFN are still not clear.

Firstly, the indirect method is introduced and proves the feasibility of using additional components to reduce the annoyance caused by LFN. A pilot EEG test indicates that EEG is a useful tool to observe the brain reaction to LFN. After that several subjective listening tests are made for LFN sufferers and subjects with different personality traits, such as noise sensitivity, mental performance, and stress situation and so on, to find out whether they have different perceptions and reactions on LFN related signals. And EEG is recorded during these listening tests to observe the corresponding brain reactions. The analysis results show that pink noise (PN) is a suitable component to combine with LFN to reduce the annoyance for subjects with high general noise sensitivity. Adding extra PN is found as a loudness decreasing effect for LFN sufferers and subjects with relative high stress levels.

The calculation of the listening test results and EEG data reveal the relations between subjective annoyance value (SAV) and the power change of EEG bands in different brain function areas. When there is only LFN related auditory stimulus, SAV shows a positive correlation with the relative power spectral density (RPSD) of Theta band at the brain function area of dealing with auditory stimuli, and a negative relation with RPSD of Beta band at the area for emotional content and auditory imagery. There are signals comprised of both visual information and auditory stimuli in the wind turbines test, besides the above relationships, a positive correlation between SAV and RPSD of Theta1 band at the position related to the function of processing emotional stimuli is also found.

The other part of this thesis is to use psychoacoustic parameters as the variables to simulate and predict the subjective feelings caused by LFN related signals. The linear regression and curve estimation calculation in SPSS shows that the evaluated loudness caused by LFN related signals can be predicted well with the psychoacoustic Loudness in linear or quadratic form. And the predicting results for SAV are various and depend on the type of the LFN signals. Psychoacoustic annoyance and the maximum value of the Fluctuation Strength are found more suitable to predict the annoyance reaction. Different personality traits show certain degrees of effects on the form and variable of the prediction. There is no significant result found for LFN sufferers in my tests, however, experiment with larger amount of this special subject group should be investigated in the future.

Acknowledgment

I would like to express my gratitude to all those who helped me during the writing of this thesis.

Foremost, I would like to express my sincere gratitude to my advisor Prof. Dr.-Ing. Detlef Krahé for his continuous support of my study and research. His guidance helped me during the time of research and writing of this thesis. I also want to thank Prof. Dr.-Ing. Jörg Becker-Schweitzer for his interest in my research and for agreeing to be the second supervisor.

I especially want to thank associate professor Lingyun Xie from Communication University of China for giving me an overview about my thesis and valuable suggestions.

I gratefully appreciate the funding received during my study and especially at the last stage from the Center for Graduate Studies (CGS). Thanks to Julian Hanebeck and Dr. Janine Hauthal for their great help.

I want to thank my colleagues Christian Kleinhenrich, Heinz Kahl, Veronika Selleschy, and Tobias Weigler for the great working atmosphere and wonderful time we spent together. With them I shared not only academic opinions but also life experience.

I especial like to thank André Leickel for his help with the wind turbine noise experiment. Thanks to Torsten Begemann for his button device used in the listening tests. Also thanks to Sabrina Skoda for her support with the ArtemiS software. And I want to thank Dr. Zhiyong Deng for his help and support of the listening test made in China.

I would like to thank Chengzong Bai, Martin Zang, Jiang Li, Si Wang, Hanyu Ye, Yihua Ye, Rui Chen, Jia Jin, Mitra Khazaei, Robert Swiatlak, Sönke Schäfer, Kathi Galla, Lorenz Meyenburg and Alex Palma for their participation in my research as the subjects.

Finally, my deep and sincere gratitude to my parents Yumei Mu and Jiaqing He for their continuous and unparalleled love, help and support all these years.

Index of Abbreviations

ACF	Autocorrelation Function
ANOVA	Analysis of Variance
APEEG	Average Power of EEG
CBT	Cognitive Behavioral Therapy
C.D.F	Cumulative Density Function
ECG	Electrocardiography
EDF	European Data Format
EEG	Electroencephalography
EOG	Electrooculography
FMETF	Forward Middle-Ear Transfer Function
FN	Frying Pan Noise
GHQ	General Health Questionnaire
GNS	General Noise Sensitivity
HP	Hearing Problem self-test questionnaire
HRQOL	Health Related Quality of Life
HVAC	Heating, Ventilating and Air-Conditioning
ICA	Independent Component Analysis
ICs	ICA components
ISO	International Organization for Standardization
LFN	Low Frequency Noise
MAF	Minimal Audible Field
MAP	Minimal Audible Pressure
NMDS	Non-metric Multidimensional Scaling
NoiSeQ	general Noise Sensitivity Questionnaire
NR	Noise Rating
PA	Psychoacoustic Annoyance
PANAS	Positive and Negative Affect Schedule
PN	Pink Noise
PNC	Preferred Noise Criterion
PSD	Power Spectral Density
PSS	Perceived Stress Scale
PT	Pure Tone
RPSD	relative PSD
SAV	Subjective Annoyance Value
SD	Standard Deviation
SN	Synthesizer Noise
SPL	Sound Pressure Level
THD	Total Harmonic Distortion
VAD	Vibroacoustic Disease
WN	White Noise
WT	Wind Turbine
WTN	Wind Turbine Noise

Contents

1 Introduction

Low frequency noise (LFN) in general means the noise with dominating low frequency energy. The boundary frequencies of LFN are not fixed, for lower limit frequency they could be at 8 Hz or 10 Hz (Poulsen and Mortensen, 2002). Because the frequency range of environmental noise is more focused on the audible part, the lower limit frequency of LFN in the thesis is set to 20 Hz. The upper limit frequency is more varied due to different purposes, for example, at 100 Hz (Krahé, 2010), 150 Hz (Penton and Chin-Quee, 2002) or 200 Hz (Leventhall, 2004). Considering the most subjects in the research are German, the upper limit frequency here is set to 100 Hz referred to the DIN45680 (DIN45680, 1997).

As we know, there is reduction due to spreading out of the sound waves and absorption over the ground or by shielding, and this attenuation increases rapidly as the frequency rises. As a result, noise which travels through long distances is normally biased towards the low frequencies. The attenuation for low frequency range requires heavy walls, and the absorption requires a thick absorbing material, which could be around one meter for frequencies lower than 100 Hz (a thickness pursuant up to one quarter of a wavelength). This is basic physical reason why LFN could be a problem, and there are also other reasons like the function of resonance, which occurs in enclosed, or partially open, spaces. Due to the correlation between frequency and wavelength of sound in the air, the wavelength of sound in 20 Hz to 100 Hz is close to a size of a normal living room, and easier causing indoor resonance and standing waves.

In this chapter, various aspects about LFN are introduced, which include the source of LFN, the effect of LFN on people, and the probable explanations for the existence of LFN sufferers. Then the standards and methods to measure or evaluate LFN are summarized. EEG as a new tool for the investigations about LFN is also described. At the end, the coping strategies against LFN are presented.

1.1 LFN sources and its effects on people

1.1.1 LFN sources

In the past, typical LFN sources were machines in factories, cooling machines, noise from the neighborhood, etc. Nowadays, the sources of LFN emerge from public infrastructures: gas transmission grids, industrial plants, road and railway traffic, sewerage, and so on. Recent inventions like district heating (citywide hot water pipeline grids for home warming and hot tap water) and underground waste transportation are added on the list (Krahé, 2012; Oud, 2012). Wind turbines are now a well-established part of a modern society's electrical generation network. On the whole, they are considered a positive benefit to society, however, due to the typical size of wind turbines and their airspace configuration, they are also classified as a typical source of LFN (Kasprzak, 2014). Statistically, the most common places with LFN problems and complaints were offices, homes, and industrial facilities (Leventhall, 2004). The LFN problems arose in quiet rural or suburban environments. Usually LFN was only heard by a minority of people; also LFN is typically audible indoors not outdoors, and more audible at night than day with a throb or rumble characteristic.

According to WHO, broadband community noise including LFN may even be a risk at low levels for certain groups such as the elderly, the hearing impaired, and children at the stage when they acquire language (Berglund and Lindvall, 1995). In 1989 local authorities in the UK received over 500 complaints of LFN a year in which nearly 90% of the complained noises were identified (Tempest, 1989). In the Netherlands most LFN complainants were older than 40 years and female (NSG, 1999). Statistically, in 2004 2.5% of the EU 15 countries' population was about 10 million people, who might have very sensitive low frequency hearing and who were prone to annoyance from sounds which were not heard by most people and which were difficult to measure (Leventhall, 2004). In China, the complaints about noise raised the proportion from 25% in 1991 to 35.6% in 1995, and a report from 2011 (MEP, 2011) stated that the traffic noise and daily life noise took larger proportion in recent years, which were mostly with low frequency components.

1.1.2 Effects of LFN on people

There are four main factors in response to LFN: auditory perception, pressure on the eardrum, perception through vibration of the chest, and a more general feeling of vibration (Leventhall, 2009). Analysis of the responses showed that auditory perception was the controlling factor. That is, although high level LFN could produce other sensations, the ear is the most sensitive receptor. LFN influences people, mainly in physiological and psychological aspects, which do not exist entirely separate, but interact with each other. For example, people who reported themselves to be annoyed by the exposure to LFN in their homes from heat pumps or ventilation installations, also reported a higher occurrence of headaches, sleep disturbance and psychosocial symptoms (Persson Waye and Rylander, 2001). The following paragraphs are some important findings about the effects of LFN on people.

- **Physiological effects caused by LFN**

Complainants of LFN sometimes reported a feeling of vibrations through their body, which indicated the possibility that body organs could resonate within the low frequency range. The study subjects were asked to identify where in their body they felt the strongest effect when they were exposed to different frequencies between 30-70 Hz. The results showed that 40 Hz was predominantly felt in the thighs and calves of the legs (77% of the subjects tested), 50 Hz was more significantly felt in the coccyx, sacrum and lower lumbar region (59% subjects tested), 60 Hz was typically felt in the thoracic area and to some extent in the lumbar region (66% of subjected tested) (Wigram, 1993).

In a field investigation among 909 subjects who answered a health questionnaire, the most frequently reported physical symptoms under the exposure to LFN and infrasound were irritation, headaches and "head feels heavy" (Nagai et al., 1989). The result of a field study with 439 persons working in offices, laboratories and industries showed that people subjectively reported reduced wakefulness or increased tiredness due to LFN (Tesarz et al., 1997). A questionnaire was made with control room workers who complained about noise in their workplace. And problems with concentration, drowsiness and headaches were reported due to noise exposure which was with low frequency components (Pawlaczyk-Luszcynska et al., 2002). Zhao investigated the effect of middle and low frequency noise on the health of electricity producing workers, and he found out that the subjects with neurasthenic syndrome of hearing injuries, symptoms like headache, dizziness, and sleeplessness among the exposed group were significantly higher than that of the control group. In the workers' cardiovascular system were also found significant difference: the symptoms were mainly hypertension, abnormal EGG and blood lipid, (Zhao, 2010).

There was an indication that long-term exposure to very high levels of LFN may cause permanent hearing loss, but the levels experienced in exposure to LFN in the normal living environment and working places were considerably lower than the levels used in the hearing loss experiments. TTS (temporary threshold shift) was found that it could occur with exposure to LFN, and the recovery period may be longer than sounds with higher pitch (Whiterod, 1972). The effect of a 24 h lorry traffic noise with a frequency spectrum in the maximum below 100 Hz was examined, and increased cortisol levels during the first half of the night among children exposed to the road traffic noise were found, compared to children in a quiet area (Ising and Ising, 2002).

Sleep disturbance is also one common complaint about LFN. In general, the symptoms of sleep disturbance include: shorter sleep duration, more frequent awakenings, increased sleep latency (e.g. difficulty in falling asleep) and downward shifts in sleep stages. The inhabitants living along a superhighway initially complained of the shaking and rattling of windows, and then became chronic insomniac and excessively tired of the continuing LFN reaching levels between 72 and 85 dBA. And the rattle caused by LFN was likely to be more disturbing than higher frequency noise (Nagai et al., 1989). In another study the cortisol response after awakening was observed and compared between exposure to LFN during sleep and in a relative quite night. The results indicated that LFN could cause the attenuation of the cortisol response (Ising and Ising, 2002).

Vibroacoustic disease (VAD) is belonging to a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to LFN. VAD has been observed in LFN-exposed professionals, such as, aircraft technicians, commercial and military pilots and cabin crewmembers, ship machinists, restaurant workers, and disk-jockeys (Branco and Alves-Pereira, 2004).

Oud said that LFN may cause endolymphatic hydrops, which may result in vertigo. He assumed that physiological process as a lymphatic flow and helicotrema blockage which could not resolve as quickly as the stop of sound. Therefore, the dizziness may persist after the LFN vanished (Oud, 2012). The objective physiological experiment and subjective questionnaire both indicated that the effect of LFN on the human body didn’t completely disappear in 15min after the subjects left the noise environment (Wang, 2006).

- **Psychological effects caused by LFN**

The primary and most frequently reported perceived psychological effect caused by LFN was not that of loudness or noisiness, but that of annoyance. As a description - “a feeling of relief” was commonly reported when LFN was turned off, even if the person was not aware of the noise when it was present (Kjellberg and Wide, 1988; Landström et al., 1991). Perceptual annoyance of LFN was measured for normal-hearing listeners and hearing-impaired listeners, and the data from both groups showed similar trends, which indicated that there was no special distinction on annoyance perception of LFN for hearing impairment (Vishnubhotla et al., 2012).

Annoyance was closely related to feelings described by the words: disturbance, dissatisfaction, concern, bother, irritation, nuisance, discomfort, uneasiness and distress (Guski, 1999; Guski et al., 1999). According to the theory of Hallmann that the factors of whether a person became annoyed when exposed to noise could be divided into the following categories: 1) individual factors (permanent and temporary) such as hearing impairment, noise sensitivity, attitude towards noise source, physiological and psychological state; 2) situational factors such as performed activities or intended to be performed; 3) sound properties such as noise level and sound characteristics (e.g. fluctuation and tonality); 4) factors related to noise sources such as controllability of the noise source, information content and permanence (Hallmann et al., 2002). Most fieldworks on noise annoyance, for example in the air or road transportation, the noise sources were known. But in particular circumstances of some LFN problems, where the noise sources were not known, these problems could add an additional element to annoyance. And the process for the affected people to locate the LFN would cause them being frustrated, which leads to extra annoyance.

Many studies found out that LFN could cause more annoyance than other kinds of noise at the same level, but without low frequency components. For example, in an experiment 24 subjects adjusted the SPL of two noise containing a high or low proportion of low frequencies in order to achieve the same level of annoyance, and it was found that LFN could have a noticeably lower A-weighted SPL than a noise not containing low frequencies and both still could be equally annoying (Kjellberg et al., 1984). A comparison between bandwidth noise peaking at 250Hz and peaking at 1k Hz with same A-weighted level showed that the annoyance from LFN was greater than that from the higher frequency noise (Persson et al., 1985). A similar result was obtained from the annoyance evaluation experiment caused by noise at same A-weighted SPL (60, 65 and 70 dBA) but with different kinds of spectra. The reactions were that exposure to ventilation noise centered at 80 Hz, was rated more annoying by 98 subjects than the noise centered at 250, 500 and 1000 Hz (Persson et al., 1990). Another listening test with eight noises run among 215 men who worked in control rooms showed that LFN at comparable A-weighted SPLs (range 48-66 dB) was rated more annoying than broadband noise without a dominant content of low frequency components (Pawlaczyk-Luszczynska et al., 2002).

- **Other influences on people**

The results from earlier studies presented that working performance was greatly influenced due to LFN. In a dual task situation investigation, the pure tones centered at 40 Hz and 100 Hz (both modulated at 1 Hz) at a level of 25 dB above the individual hearing threshold were found that they caused more errors than a narrow band noise centered at 70 Hz with the same level and a recorded traffic noise (90 dB Lin). The effect was especially pronounced during the last ten minutes of the total 30-minute exposure (Benton and Leventhall, 1986). A lower learning rate was found in a demanding verbal, grammatical reasoning task when the task was performed during exposure to simulated ventilation broadband noise (15-1000 Hz, 51 dBA, 57 dBD) with a dominance of energy in the low frequency range (Kjellberg and Wide, 1988). In the conditions of narrow band LFN at 70 dBC and 95 dBC, subjects were found having more semantic and spelling errors on a proofreading task (Benton and Robinson, 1993). And ventilation noise dominated by low frequencies was found to increase the time taken to respond to a verbal reasoning task, when compared with a similar noise of equivalent loudness with much less low frequency energy (Persson Waye et al., 1997).

In the PhD thesis of Bengtsson, she found that LFN could lead to specific performance impairments such as in tasks with high and moderate demands on cognitive processing when carried out under high workload or in tasks with moderate and low demands when these were performed under low workload. The accusations were hypothesized by impaired learning and reduced attention due to LFN (Bengtsson, 2003). The main influences of LFN from typical air conditioning in offices, left the employees broken in their work, gave them difficulties to concentrate, kept them of entering a working state, easily agonized them and caused dizziness, but respectively no disturbances with the employees short-term memory were reported (Yu, 2006). In addition, LFN had also certain effects on communication, pitch discrimination, brain stimulation, and in the entertainment field (Broner, 1978).

1.2 LFN sufferers

The same noise could result in totally different responses by different people depending on cultural factors (Kuwano et al., 1991), activity time of the exposure (Borsky, 1980), attitude to the noise source (Fields, 1993), noise sensitivity (Job, 1988; Stansfeld, 1992), the controllability of the stressor (Evans, 1982), and other individual differences. People who are very sensitive to LFN or who cannot tolerate LFN have been recognized as a separate category of “LFN sufferers”, although an “LFN response syndrome” has not yet been defined. The number of LFN sufferers is rising recently. In some cases, LFN sufferers were the only person in a family who could hear the noise (Leventhall et al., 2008). Some reported that other people who came to their residence could also hear the LFN, but could bare it and the noise did not bother them as much as it did the complainants. Adam interviewed and made questionnaires with LFN sufferers, and he found that 92% of the complainants reported themselves suffering from sleep disturbance, 83% suffering from stress, and 67% having difficulty in falling asleep. Insomnia, depression, heart ailments, headaches, migraines, high blood pressure were also the main reported symptoms (Adams et al., 2007).

One possible explanation about ‘why one person can describe a LFN as loud and annoyed while another cannot even hear it?’, is based on how the human hearing system operates on low frequency. The perceived loudness of low frequency sounds increases very rapidly with increasing acoustic energy. Therefore, low frequency sounds just above the threshold of hearing can be perceived as loud, even uncomfortably loud. The hearing threshold is the median value for ontological normal young adults. Consequently, 50% of the subjects have a threshold that is more sensitive than the median and 50% have a less sensitive threshold (Leventhall, 2009). So when a low frequency sound is above one person’s threshold, it could be heard and perceived to be relatively loud, but it is possibly below the threshold of another person with less sensitive hearing at the low frequency range, who therefore cannot hear it at all. The extraordinary low hearing threshold of low frequency sound might be explained by abnormalities in the person's hearing organs that an abnormally small aperture in the helicotrema at the apex of the cochlea creates. For low frequency sound the helicotrema acts like a kind of pressure equalization vent for the perilymph in the cochlea, equalizing the pressure between the scala tympani and the scala vestibule. When the helicotrema is unusually narrow or blocked, then it cannot equalize the pressure fast enough, and an unusually high pressure will build up between the scala tympani and the scala vestibule (Schick, 1994).

The LFN sufferers were supposed to be more sensitive to the low frequency sounds than the others, that is to say, they should have lower hearing threshold in the low frequency range. However, the measurement results did not support this hypothesis. It was ascertained that there was little difference between the low frequency thresholds of those who complained of LFN and those who did not (Walford, 1983). In another study the hearing threshold at the low frequency range for LFN sufferers was found not lower than that for the reference group (Poulsen and Mortensen, 2002). Significantly, for the reference group there was a clear connection between the noise level and the experienced annoyance, but for the LFN sufferers group this connection was less clear, especially at night they rated the annoyance as close to maximum and thus not dependent on the level of the noise.

Although there was no special low frequency hearing threshold found in LFN sufferers, some interesting findings were obtained in the other researches. Inukai and his colleagues investigated the characteristics of the LFN sufferer thresholds and their acceptability of low frequency pure tones of frequencies from 10 Hz to 100 Hz. So they learned that all LFN sufferers could be characterized by an extremely narrow range between their hearing threshold and the acceptable limit to a low frequency tone (Inukai et al., 2005). In addition Kurakata found that many older people retained good hearing ability in the low frequency region, but with often-degraded sensitivity at higher frequencies. And this imbalance of hearing sensitivity could let them react more sensitively to low frequency sounds than younger people do (Kurakata et al., 2008).

Tinnitus was often used as one possible and conventional explanation for LFN suffering. Walford tried to separate the LFN sufferers and tinnitus sufferers from a listening test, which included adjusting the frequency, throb rate and amplitude of an oscillator, and another earmuff test (Walford, 1983). An important result of this work was about the memory matching of LFN. When the matching sounds were on the levels as the LFN sufferers heard them in their homes, the levels of the noise were all above average threshold levels, in many cases by 20dB to 40dB. When the matching levels were correct, the effects were likely to be tinnitus, and the subjects matched how they felt about the noise, rather than what they heard.

There are also other possible explanations for LFN sufferers. For example, the results of a preliminary study to compare the objectively measured forward middle-ear transfer function (FMETF) with the actual perception of LFN showed that a person who was annoyed by LFN could have the dip of the resonance feature at a prominent frequency of the noise, where the other person could have a peak, which could lead to a very significant difference in perceived loudness (Pedersen and Marquardt, 2009). Another explanation was that when people listened to an unwanted noise for a considerable period of time and developed an aversion to the noise, they may also develop enhanced hearing sensitivity to this noise. The elder generation was exposed longest to the noise of public infrastructure, and a prevalence of LFN complaints increasing with age was agreed with this assumption (Leventhall et al., 2003). This conception was similar to the hypothesis that long-lasting exposure to LFN could alter the cochlea, and LFN could become audible from inaudible to the exposed person. This alteration was verified in testing laboratory animals. Besides, electromagnetic waves and synesthesia effect from other perceptions were also used as the explanations for some particular cases.

1.3 Standards and methods for the measurement and evaluation of LFN

Since the appearance and increasing of the complaints and problems caused by LFN, the methods to identify LFN, finding its source, measuring the characteristics of the noise, assessing or evaluating the damage caused by LFN, and predicting its effects were developed to help people to better deal with LFN.

1.3.1 National standards and noise rating curves

Some countries adopt national criteria for LFN, including Germany (DIN45680, 1997), Denmark (Jakobsen, 2001), Sweden (Socialstyrelsen-Sweden, 1996), Poland (Mirowska, 2003), Netherlands (NSG, 1999; Sloven, 2000), and UK (Moorhouse et al., 2005) and more. Some of these standards propose a threshold curve for the limitation of annoyance based accordingly on the ISO226 threshold, or a curve parallel to this threshold but extended to frequencies below 20Hz. These methods and criteria are used in different situations to assess the annoyance due to LFN, and give different guidelines on the allowed noise level. Table 1.3.1 shows the limitation values of different national standards.

- **German Method**

In the German standard (DIN45680, 1997), LFN is defined as noise where the C-weighted noise level is at least 20 dB higher than the A-weighted level, based on either equivalent levels or maximum levels. If the noise is evaluated to be ‘low frequency’, a 1/3-octave frequency analysis is made. The method considers the frequency range from 10 Hz to 80 Hz, but in special situations the 8 Hz and/or the 100 Hz band can be included. The method applies to rooms in dwellings where people stay or rest. And a range of limit or criterion values are given for the day period (06 h – 22 h) and for the night period (22 h – 06 h). Particularly, a distinction is made between tonal noise and noise without tones. If the level in a particular 1/3-octave band is 5 dB or more above the level in the two neighboring bands, the noise is described as tonal.

For tonal noise, the level of the frequency band with the tone is compared to the hearing threshold in the same band. It is then found how much the tone is above the threshold. The levels in the other frequency bands are not taken into account. The limit value for the equivalent level of the tone in the day period is: 5 dB in the 8 Hz - 63 Hz bands, 10 dB in the 80 Hz band, and 15dB in the 100 Hz band. The same assessment method applies to the maximum level of the noise. In the night period all the limits are reduced by 5 dB. If the noise is not tonal, the limit for the A-weighted equivalent level (10 Hz - 80 Hz) is 35 dB during the daytime and 25 dB during the night. The A-weighted level is calculated by adding the A-weighting corrections for only those levels that are above the hearing threshold. The corresponding levels for the maximum levels are 45 dB and 35 dB.

- **Danish Method**

The Danish method gives the recommended limit values for LFN and infrasound. The noise is measured in several positions indoor and is analyzed in 1/3 octave bands. The A-weighting corrections are added to the spectra, and the weighted spectrum is summed to form the A-weighted level of the noise in the frequency range from 10 Hz to 160 Hz (Jakobsen, 2001).

- **Swedish method**

The recommendations from the Swedish National Board of Health and Welfare give guidance to an assessment of whether noise under different conditions may have health effects. It comprises a criteria curve of recommended maximum levels of LFN in rooms used for living. The curve covers the frequency range from 31.5 Hz to 200 Hz and applies to the equivalent level of the noise. If the noise level exceeds the criteria curve in any 1/3-octave band, the health and environmental authorities may characterize the noise as a sanitary nuisance (Socialstyrelsen-Sweden, 1996).

- **Polish Method**

Polish method is defined in the frequency range from 10 Hz to 250 Hz, and corresponds to 1/3-octave levels each giving an A-weighted level of 10 dB (i.e. 10 dB above the inverse A-weighting correction). The criterion curve is called L_{A10} (Mirowska, 2003). LFN is considered annoying if both of these conditions are met: the spectrum of the noise exceeds the criterion curve L_{A10} in one or more 1/3 octave bands and exceeds the spectrum of the background noise by 10 dB for tonal noise or 6 dB for broadband noise.

- **Netherlands Method**

One proposed method (Sloven, 2000) is intended to use along with granting environmental permission to industries and enterprises. It is defined in the frequency range from 10 Hz to 200 Hz and is close to the German method below 40Hz and then corresponds with the Swedish method. It is expected that annoying LFN will occur if the criterion curve is exceeded in one or more 1/3-octave bands. The other method is for audibility not annoyance (G.P. van den Berg, 1999). Audibility is based on hearing thresholds for the 10% most sensitive people in an otologically unselected population aged 50-60 years. The obtained thresholds are typically about 4-5dB lower than the average threshold for otologically normal young adults (18-25 years) as given in ISO226.

- **UK method**

L_{eq}, L_{10} and L_{90} in the 1/3 octave band between 10 Hz and 160 Hz are required to measure in the UK method (Moorhouse et al., 2005). If the L_{eq} exceeds the reference values, it may indicate a source of LFN that could cause disturbance, and consequently the character of the noise should be checked. If the LFN occurs only during the day then 5dB relaxation may be applied to all third octave bands. Or if the LFN is steady (L_{10}-L_{90} < 5 dB, or the rate of change of sound pressure level is less than 10 dB/s), then a 5 dB relaxation may be applied to all third octave bands.

Table 1.3.1 The limitation values of the national standards for LFN

	Germany	**Denmark**	**Sweden**	**Poland**	**Netherlands**	**UK**	**ISO226**
Frequency (Hz)	dB	NSG dB	dB	L_{A10} dB	dB	L_{eq} dB	dB
8	103						
10	95	90.4		80.4		92	
12.5	87	83.4		73.4		87	
16	79	76.7		66.7		83	
20	71	70.5		60.5	74	74	78.5
25	63	64.7		54.7	64	64	68.7
31.5	55.5	59.4	56	49.3	55	56	59.5
40	48	54.6	49	44.6	46	49	51.1
50	40.5	50.2	43	40.2	39	43	44
63	33.5	46.2	41.5	36.2	33	42	37.5
80	28	42.5	40	32.5	27	40	31.5
100	23.5	39.1	38	29.1	22	38	26.5
125		36.1	36	26.1		36	22.1
160		33.4	34	23.4		34	17.8
200			32	20.9			14.4
250				18.6			11.4

In Europe it was also common to use Noise Rating curves (NR), which was developed by the International Organization for Standardization (ISO), to determine the acceptable indoor environment for hearing preservation, speech communication and annoyance (Kosten and VanOs, 1962). The noise rating graphs were plotted at acceptable SPLs at different frequencies. But NR curves were found not suitable to assess high level LFN, and then the spectrum was expanded to 16 Hz known as the NRM curves (Challis and Challis, 1978). NR curves were also modified in the low frequency region, leading to the LFNR curves, which impose low frequency penalties. In LFNR curves, the determination of the appropriate rating curve was in the normal way for frequencies above 125Hz, and when the spectrum of frequencies below 125Hz exceeds this rating curve, it was suggested that there was the potential for a low frequency problem (Broner and Leventhall, 1983). In addition, Preferred Noise Criterion curves (PNC) were used to judge the acceptability of ventilation and other background broadband noise (Beranek et al., 1971). Beranek also proposed NCB curves, which expanded the PNC curves from 31.5Hz to 16Hz (Beranek, 1989).

1.3.2 Psychoacoustic parameters functions

In general, octave band and power spectrum analysis are the fundamental tools to find the physical property of LFN. However, both analyses are insufficient for describing the sound quality characteristics (Kwan ryu et al., 2008). In many cases, LFN sufferers complained about LFN even with relatively low SPL. Sometimes they misunderstood higher frequency noise for LFN as the reason of annoyance. And some LFN sufferers with tinnitus also complained even when no low frequency component could be found in their living environment. These indicate that besides SPL and power spectrum analysis, acoustical parameters related to psychological perception should be considered to better understand LFN complaints.

The psychoacoustic parameters were designed to quantify the listener's perception and evaluation of sound quality (Fastl and Zwicker, 2007). These parameters were used as sound quality indices for noises, mainly stationary ones, and also found useful for LFN studies. For example, tonal components in the low frequency range were found highly related to subjective response, and loudness for low frequency components below 100 Hz were more highly correlated with fluctuation perception with lower modulation frequency (Kwan ryu et al., 2008). The loudness-based impulsiveness had a strong relationship with the perceived annoyance of impulsive sounds for IT devices, and this psychoacoustic parameter was recommended to assess and improve the sound quality of products which emitted significant impulsive content (M. Willemsen and D. Rao, 2010). The annoyance of vacuum cleaner noise which had strong energy at the low frequency range, depended on loudness, sharpness, roughness, fluctuation strength, tone-to-noise ratio, and prominence ratio (Altmsoy et al., 1999). Sottek and Genuit developed a ‘Hearing Model’ for sound quality evaluation of a fan noise, and they found out that tonal components and modulated sounds were often the causes of customer complaints (Sottek and Genuit, 2007). A sound quality metrics for predicting the perceived annoyance of automobile power windows was developed, and it was proposed that product quality could be predicted by low pass loudness and SPL based sharpness (Nykänen and Sirkka, 2009).

Among the findings about the relations between psychoacoustic parameters and subjective feelings caused by noise, especially by LFN, the comparison and correlation results of the subjective annoyance value (SAV) from listening tests and the psychoacoustic annoyance values (PAV) according to the semi-theoretical formulas from Zwicker and Fastl’s theory, had a strong influence on this thesis. The results suggested that PAV could be used to predict SAV variance of LFN combined with pink noise, and it was also possible to use when searching for the appropriate pink noise combined with LFN to alleviate subjective annoyance (Di et al., 2011).

1.3.3 Other methods

Besides national criteria and the predicting method with psychoacoustic parameters, there were also some curves and means for LFN assessment or LFN rating. These findings were usually according to the results from a large number of laboratory experiments, which used stimuli included low frequency tones, bandwidth LFN, and recordings of LFN in sufferers' working places or homes. The responses required from subjects varied from experimental methods. Commonly, the subjects were asked to "imagine" themselves relaxing in their homes at daytime or in the evening and to rate annoyance by, for example, choice on a semantic scale ranging from 'not annoying' to 'extremely annoying'. On the other hand, they needed to mark the level of annoyance on an unnumbered linear scale at a point between these two extreme above, or assigned a number to a reference noise, or gave appropriate numbers for other noises in order to estimate their magnitudes. The following paragraphs are some samples of the experimental findings.

Møller investigated contours of equal annoyance for pure tones in the frequency range 4 Hz to 31.5 Hz (Figure 1.3.1). The annoyance contours were influenced by the narrowing of the range of equal loudness contours at low frequencies (Møller, 1987). Inukai proposed LF and LF2 curves (Figure 1.3.2) to be separated as assessment for low level and high level LFN (Inukai et al., 1990).

The spectrum balance induced by LFN influenced on the subjective perception. For example, it was found that LFN with spectrum of an averaged fall off above 32 Hz of 5.7 dB/octave was acceptable, whilst a fall off from 63 Hz at 7.9 dB/octave was unacceptable (Figure 1.3.3) (Bryan, 1976). A similar conclusion showed the work of Blazier for air conditioning noise that on average acceptable office environments had a fall off of 5 dB per octave (Blazier, 1981).

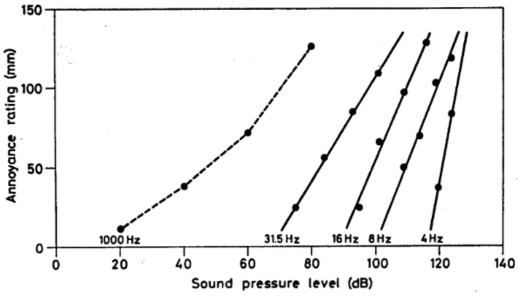


Figure 1.3.1 The equal annoyance curve for low frequency pure tone (Møller, 1987)

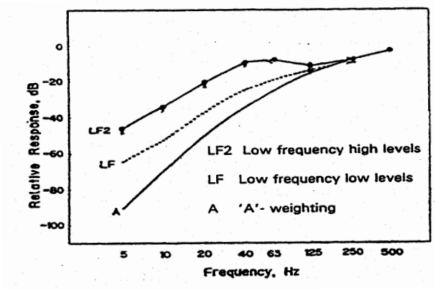


Figure 1.3.2 The assessment curves for low level and high level LFN (Inukai et al., 1990)

Broner and Leventhall measured an individual annoyance function for LFN with 20 subjects and suggested that annoyance could have a simple relation with stimulus intensity and subject personalities. The function was set as $\psi = k\varepsilon^{\beta}$, with ψ represented the estimation of psychological magnitude, ε for the stimulus intensity and β as a subject-specific exponent. A wide range of individual exponents was obtained, which could be from 0.045 to 0.4 (Broner and Leventhall, 1978).

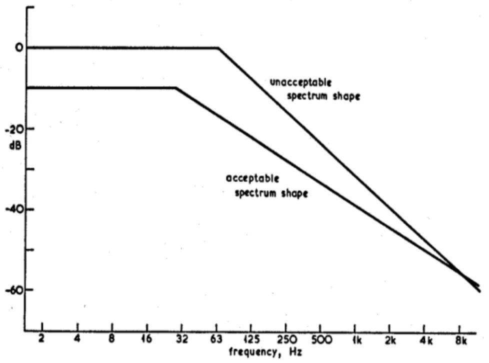


Figure 1.3.3 The acceptable and unacceptable spectrum shapes (Bryan, 1976)

Besides the annoyance caused by LFN, the “unpleasantness” caused by LFN was also estimated. The “equal unpleasantness” contours were determined with 39 subjects over a tone frequency range of 10 Hz to 500 Hz in five scale levels. All levels of unpleasantness were approximately linear with a negative slope of 5-6 dB per octave (Inukai et al., 2000; Nakamura and Inukai, 1998).

1.4 EEG observation under noise exposure

As we know, noise is defined as undesired sound, but noise and sound are physically the same, differences arising in their acoustic quality as perceived by listeners (Leventhall, 1998). Sound is detected by the ear in a mechanical process, which converts the sound waves to vibrations within the ear, and then auditory nerve fibers transmit the signals sent from the cochlea to the brain, in where numerous relay stations (groups of neurons) receive the signals and decode them in order to cause a sensation or conscious perception. The responses to sound are very individual, which could depend on many personal and situational factors, and can be conditioned by both previous experiences and current expectations. Subjective evaluation obtained through psychological measurements is generally used to quantitative evaluate people’s assessment to an acoustic environment. In addition, it is also important to objectively observe, from physiological aspect, human reactions to surrounding environments (Tsujimura and Akita, 2012).

Electroencephalography (EEG) is one of the most complex biological signals used in medicine, and an important way for the investigation of the physiological and psychological condition of the participants. In general, EEG is obtained using electrodes placed on the scalp with a conductive gel and it reflects the electrical activities of brain neuron in the cerebral cortex and scalp. The human brain contains millions of neurons, each of which generates small electric voltage fields, and the aggregate of these electric voltage fields creates an electrical reading which electrodes on the scalp are able to detect and record. Therefore, EEG is the superposition of many simpler signals and it has the amplitude range typically from about 1 µV to 100 µV for a normal adult.

With billions of oscillating communities of neurons as its source, the human EEG potentials are manifested as aperiodic unpredictable oscillations with intermittent bursts of oscillations having spectral peaks in certain observed bands. For healthy adults, the amplitudes and frequencies of such signals change from one state to another, such as between wakefulness and sleep, and the characteristics of the waves also change with age. There are five major brain waves distinguished by their different frequency ranges, from low to high frequencies respectively are called Delta (δ), Alpha (α), Theta (θ), Beta (β), and Gamma (γ) (Saeid Sanei and J.A. Chambers, 2007).

- **Delta waves** (δ) - They are primarily associated with deep sleep, and are very easy to be confused by artefact signals caused by the large muscles of the neck and jaw, therefore, Delta waves are not considered here.
- **Theta waves** (θ) - They appear as consciousness slips towards drowsiness, and are associated with access to unconscious material, creative inspiration and deep meditation. The changes in this rhythm are examined for emotional studies.
- **Alpha waves** (α) - They could appear in all over the head, higher in amplitude on the dominant side. Alpha waves have been thought to indicate a relaxed awareness without any attention or concentration. The International Federation of Societies of Electrophysiology and Clinical Neurophysiology (IFSECN) define Alpha rhythm as the rhythm occurring during wakefulness over the posterior regions of the head, with generally maximum amplitude over the occipital areas. The amplitude varies but is mostly below 50 µV for adults and they are best seen with eyes closed during physical relaxation and relative mental inactivity, and blocked or attenuated by attention, especially with visual or mental efforts. They are also found reduced or eliminated by hearing unfamiliar sounds.
- **Beta waves** (β) - A Beta wave is the usual waking rhythm of the brain associated with active thinking, active attention, or solving concrete problems. The amplitude of Beta rhythm is usually less than 30 µV, and a high-level Beta wave may occur when a human is in a panic state.

The amplitude of higher frequencies (gamma range) is normally very low and their occurrence is rare, so they are also not included in the research.

The cerebral cortex plays a key role in memory, attention, perception, awareness, thought, language, and consciousness (Kandel et al., 2000). It can be classified on the basis of gross topographical conventions into four lobes: Frontal lobe, Parietal lobe, Occipital lobe, and Temporal lobe. Different neocortical regions known as Brodmann areas are distinguished by variations in their histological structure and functional roles in sensation, cognition and behavior (Brodmann, 1909). The details of cerebral cortex and Brodmann areas involved in the thesis will be described in the Chapter 2.

There were many experiments using EEG as the tool to find out how a person's brain reacts to music, noise or visual stimulus, and some were related to the disturbance of noise on sleep. Earlier research results of human brain physiology showed that brain activities occurred simultaneously with external stimulation (Walter et al., 1946). For example, the auditory information process was found affected by the priority of processing in the brain, and the results demonstrated that EEG was effective for objective evaluation as a physiological index (Akita et al., 1995). Higher activation in auditory cortex was found in response to unpleasant sounds relative to neutral sounds (Viinikainen et al., 2012).

The main studies and findings about using EEG to observe the brain reaction under LFN exposure were in two aspects. One was the relation between the character of LFN and the power changes of different EEG bands, which meant to observe the brain reaction due to the appeared LFN or compare the brain responses to different noise types. For example, EEG changes in wakefulness and exposure to low frequency and high frequency noise were investigated, and the correlation between the tiring effect of LFN and the individual EEG signals was found. There were three control periods and two experimental periods each for 15 minutes in the experiment with subjects' eyes closed. The results indicated a reduction in wakefulness during exposure to a repeating 42 Hz (70 dB) signal and an increasing in wakefulness during a repeating 1000 Hz (30 dB) signal. Although the changes in EEG were variable and non-significant, there was a suggestion that the Theta activity had increased with the eyes closed and LFN could produce weariness (Landström et al., 1985). The brain reactions under exposures of continuous, regular and irregular intermittent noise consisting of three kinds of unpleasant noises (frying pan noise (FN), synthesizer noise (SN) and white noise (WN)) and pure tones were estimated with EEG (Saito, 1988). The results indicated that the effects of noise on higher nervous activity could differ not only as a result of the levels of the physical energy, but also according to the conditions of their generation. And when a subject indicated discomfort, the Alpha wave decreased and slow waves increased. In sensory regions, Alpha oscillations were found as the dominant rhythm at rest condition, and its power decreased when actively engaged in processing or even anticipating a stimulus. So the Alpha decrease in auditory cortex was assumed to accompany the presentation of external sounds (Weisz et al., 2011). A similar result was obtained from a tinnitus research. There, reduced Alpha power was related to an increased phantom sound sensation (Müller et al., 2013). Alpha band activity was found greater under noise exposure in low or high frequency range than that in no sound. On the other hand, Beta band activity was in an opposite change trend (Cho et al., 2011).

The other aspect of the experiments was about the relation between the subjective feelings caused by LFN and EEG variation. For example, the relation between EEG variation and subjective annoyance was investigated with 70 dBA white noise and pure tones at 160 Hz, 500 Hz and 4000 Hz being selected as exposed noise sources (Li et al., 2014). When the duration of the sounds was less than 6 s, the relative average power of EEG (APEEG) did not change much regularly. But when the exposure duration was for 5 min, the relative APEEG variation of Theta and Alpha waves in the frontal region exhibited regularity, and the time points of the maximum APEEG value of the Theta wave occurred related to the frequency of the pure tone. This result indicated that the time for subjects to make steady stress responses tended to decrease with the increase of frequency. The sum of the APEEG of Theta and Alpha waves in the frontal region was found to increase with the increasing of the subjective annoyance level. The auto-correlation function of Alpha activity during the presentation of annoying sound was analyzed to investigate the annoyance responses to noise, and the differences in alpha persistence between subjects with high and normal noise sensitivity provided information on how annoying sounds were perceived (Lee et al., 2012).

Considering that there were not a lot of EEG experiments using LFN as the stimulus to find out the relation between the produced emotions and brain reaction, the findings using other sounds as the stimuli were summarized as the reference. The left hemisphere was found superior in the processing of positive emotions, while the right hemisphere was for negative emotions (Sutton and Davidson, 2000). This hypothesis was supported by many researchers, for example, the left frontal EEG activity (Alpha band) showed a greater relationship with joy and happy musical excerpts, and the greater relative right frontal EEG activity was found for fear and sad musical excerpts (Schmidt and Trainor, 2001). And the results of another research which used complex auditory stimuli (short sequences of jazz, rock-pop, classical music and environmental sounds) to investigate EEG activation for both hemispheres showed that a highly significant lateralization effect occurred as pleasant evaluated sounds produced more left temporal activation and negatively attributed sounds were connected with a more bilateral pattern, with an emphasis on the right front-temporal areas. And female subjects showed greater valence-related differences than man (Altenmüller et al., 2002).

More Beta activity was present in the right temporal area during positive than negative emotional tasks (Ray and Cole, 1985), and the authors also proved that Beta wave might be a useful measure of appropriate cognitive and emotional processes. Theta activity was found evidently increased in the frontal region of the brain during the auditory-comprehension task (Adjouadi et al., 2004). The increase of Alpha oscillations in visual areas was found involved in processing distracting information (Thut et al., 2006).

Stress is also a kind of subjective feelings, which could be caused by LFN. In the study, about the long-term exposure to an audible low-level LFN, which was classified as a background stressor, the result showed that the constant LFN could cause chronic psychophysiological damage (Leventhall et al., 2003). It is known that when a person is exposed to a physical or psychological stressor, the brain initiates a stress response, and follow with a series of chemical reactions. The findings from the investigations about the relation between stress level and

EEG variation were summarized as follows. Beta activities in the frontal and temporal areas of the non-stress group were significantly larger than those of the stress group under emotionally unpleasant stimuli. Also the Beta activities of the non-stress group decreased with time (Hayashi et al., 2009). The right prefrontal cortex was assumed involved in the response to stress, due to its character as a fundamental component of both the emotional and vigilance networks (Seo and Lee, 2010). It also suggested that inter-individual differences under stress could be reliably assessed by EEG, and stress patterns could be indicated by high Beta power and low Alpha power on the anterior side of the human brain (FC5, FC6). A similar result was observed that stronger stress response was linked with the reduction of relative power of Alpha waves in the parietal and occipital lobes, and an increase of the relative power of theta waves with noise as the major factor of stress (Park et al., 2011).

1.5 LFN coping strategy

Considering the above description of the physiological and psychological impacts caused by LFN, the LFN complaints must be taken seriously at both human and resource aspects. And due to age-related onsets of LFN complaints and a demographic trend of an aging population, it could lead to a prediction of increasing LFN sufferers in the future. Not like other kinds of noise, experience of controlling and solving the problems which led to complaints about LFN were not very promising. Some complainants chose to endure the problem, continued to suffer without further complaints to external authorities, and some made demands on resources but with no effect, which were all unsatisfactory. Only a very small number of LFN sufferers were known to improve their situations by changing or controlling their attitudes to LFN, or finding their own ways to reduce the negative impacts caused by LFN.

Many investigations suggested that coping strategies against LFN could evolve the ways like: consulting from other sufferers who had accommodated to their noise, learning the techniques from tinnitus management specialists, getting recommended strategies for management LFN problems from health organizations, developing training programs for personal advice for sufferers etc. In some cases, one strategy was found useful. It was to stop fighting the noise and relax one's physical and mental responses to it (Leventhall et al., 2003). Adams and his colleagues collected the coping strategies that the sufferers developed to against the LFN. Half of the LFN sufferers tried earplugs for sleeping and some found them helpful and used them at night. Headsets or ear defenders were tried by a third of sufferers. Three quarters of the complainants tried sleeping in different rooms in their house with varying degrees of success. Some attempted to put foam under the bed legs, with no effect, while others slept with their head pointing towards the middle of the room rather than against the wall, with some effect. Creating additional noise to mask the LFN was tried by some, again with varying success (Adams et al., 2007).

Another project which produced a training program included CD vision and online teaching also obtained a certain degree of help for LFN sufferers (Department for Environment Food and Rural Affairs, 2009). Firstly, the subjects assessed psychologically to place themselves within the introvert-extravert framework, and then they needed to complete questionnaires for their quality of life and coping ability. Cognitive Behavioral Therapy (CBT) was the main idea to enable participants to learn methods of coping with LFN. In the program, there were five lessons: 1) introduction and preparation; 2) building motivation and monitoring progress; 3) desensitization to sounds; 4) healthy thinking about sounds and 5) learning to sleep better. And from the feedback of the users, the project was confirmed helpful for LFN sufferers dealing with their problems. Comparison of before and after results showed that using the subjects as their own controls could get a positive effect. This method was suggested not limited to LFN and could also be possible for the disturbance by other environmental noises.

There were other kinds of coping strategies from the results of subjective evaluation listening tests, which obtained decreasing the annoyance caused by LFN via masking effect or frequency balance conception. For example, adding pink noise with a frequency band located within the same frequency range as the tone of the ventilation noise itself may improve the subjective perception of the noise (Landström et al., 1992). A suitable spectral balance could improve the positive impressions of the interior truck sound (Genell et al., 2006). Krahé gave two explanations for the extreme annoyance caused by LFN with weak high frequency components. One was about the adaptation in the inner ear of the strong fluctuation character of this kind of noise, and the other could be a strong synchronism in the activities on the nerve fibers. And from the simulation of the auditory system with computer models based on this hypotheses, the synchronism disappeared when some components at higher frequencies were added (Krahé, 2012). Similarly, sounds with higher frequencies were found that could suppress the response of the cochlea to very low frequencies (Salt and Lichtenhan, 2011). The ear's response to LFN was influenced by the presence of higher-frequency sounds such as those in the speech frequency range, with substantially larger responses generated when higher-frequency components were absent (Salt and Lichtenhan, 2012).

An indirect method which was named as "Sound Adjustment" to decrease the negative effects on the side of LFN sufferers was proposed and the feasibility was proven (Di et al., 2011; Li, 2012). This method was not like the traditional and the direct noise control which was mainly to reduce the SPL of the LFN. The idea was to improve the subjective feelings of the sound environment in an indirect way by changing the spectral structure, sound quality, and the soundscape. One main assumption of the sound adjustment method for LFN was to find suitable sounds as the additional components to combine with the original LFN, thereby to reduce the annoyance caused by LFN. FM pure tones with different central frequencies and natural sounds (including the sound of singing birds, flowing water, and the wind or a ticking clock) were tested as the practical ones (Di et al., 2011), but only an FM pure tone of 15 dB with a central frequency of 2000 Hz and a modulation frequency of 10 Hz was found to produce a lower subjective annoyance value (SAV). The SAV of LFN combined with the pink noise in a bandwidth of 250 Hz to 1000 Hz with SPL from 15 dB to 25 dB was found lower than that of the original LFN. When adding a sound of flowing water, especially that containing fewer low frequency components, the subjective annoyance could be effectively reduced. In addition, the dosage exercise test result from behavior disturbance tests indicated that the brain-work index (AYP) rose, while the error rate fell when the subject was exposed to the adjusted samples, which proved that adjustment for LFN could indeed reduce the negative impact on people's thinking ability.

1.6 Research direction and contents

In summary, LFN is a kind of environmental noise that exists around people and can hardly be avoided. A great deal about LFN is known through a lot of investigations and experiments, for example, its negative effects on human physiological and psychological aspects are an indisputable fact but many of the situations cannot be understood. It is clear how people hear LFN from the anatomical aspect, but it is unknown how the brain deals with it. The amount of LFN sufferers shows a growing trend, but the LFN in many complaints cannot be measured separately from the background noise. The evidence shows that LFN is more annoying than the other kinds of noise, but the exact reason is still unclear.

There are two main aims in this thesis. One is to understand why LFN sufferers have different perception and reaction on LFN compared with others. The observation is designed in subjective and objective aspects. The subjective evaluation listening test could obtain the direct annoyance reaction from the subjects, and the assessments are supposed to relate to the character of LFN, the individual experience, different personality traits such as noise sensitivity, mental performance, and stress situation. The hypothesis is that there are different subjective annoyance results from the same LFN between LFN sufferers and the reference subjects, also between participants belonging to different personality traits groups. The objective investigation is the brain reaction observation under LFN exposure. The hypothesis is that the same LFN could cause different brain variations for different subjects, which could be presented in the power changing of EEG bands. Since the annoyance caused by LFN is supposed to be a performance form of the brain reaction, in theory, there are relations between the annoying level and power changing of EEG bands in different brain function areas. During the analysis, different personality traits obtained from questionnaires are also supposed to show certain effects.

The other aim is to find out a suitable method to predict the subjective feelings caused by LFN, such as annoyance and loudness. The simulation uses the psychoacoustic parameters and the results from listening tests as the database. By means of the calculation between subjective evaluation results and the characters of the LFN, it is supposed to find out the suitable models for LFN sufferers, the reference subjects and also for subjects with different personality traits to predict their responses to LFN related noise.

Therefore, the next dissertation is arranged as follows:

Chapter 2 describes the questionnaires appearing in all experiments, which include the basic hearing ability, sensitivity for LFN and general noise, mental performance and stress situation. It also introduces the devices for presenting the auditory and visual stimuli, plus the different EEG devices. The last part is the general procedure of EEG measurement, and EEG data analysis methods.

Chapter 3 presents five experiments, which include subjective listening tests and EEG measurements. There are information about the joined subjects, experiment material, used method and data analysis for each experiment. Different conclusions of the perception and reaction on LFN in subjective and objective aspects are given in this chapter.

Chapter 4 proposes the idea of using psychoacoustic parameters to predict the annoyance and loudness feelings caused by LFN related signals for LFN sufferers and the reference subjects, as well for subjects with different personality traits. The correlation and regression calculations are made to obtain the relations and suitable models.

Chapter 5 gives the discussions and conclusions based on the findings of all the experiments and outlines some recommendations for future investigations.

At the end of this thesis is a bibliography including the references, the index of the questionnaires tables as mentioned in chapter 2 and some results of the experiment in chapter 3, list of tables and figures, and publications that were written while conducting research for this thesis.

2 Questionnaires and experiment devices

The first part of this chapter is the introduction of the questionnaires appearing in the experiments, which included the personality traits, sensitivity to the general noise and LFN, the mental performance and behavior in stress situations. The choice and reasons for these questionnaires and how to use them in the listening test and EEG test are also given. The second part is the information about devices for the auditory and visual stimuli replay. The last part is about the EEG devices, relevant principle and processing methods for EEG measurement and data analysis.

2.1 Questionnaires

One common theory is that handedness affects the hemispheres, and left-handed people have a reversed brain division of labor (Banich, 1997). Emotional activation showed that it could produce measurable effects on the EEG, and it was hypothesized that personality traits would interact with strength (Stenberg, 1992). Therefore, it was necessary to classify the subjects into different groups depended on their personal characters to observe whether there were different perceptions and reactions on LFN between the groups. Before the listening tests or EEG measurements the subjects were asked to answer some of the following questionnaires: Edinburgh inventory (L/R handedness), General health questionnaire (GHQ-28), General noise sensitivity questionnaire (NoiSeQ), LFN sensitivity questionnaire, PANAS and the Perceived Stress Scale (PSS-10). The questionnaire tables are in Appendix 1.

- **Edinburgh inventory**

The Edinburgh inventory is a measurement scale used to assess the dominance of a person's right or left hand in everyday activities, and has been used in various scientific studies (Oldfield, 1971).

- **General health questionnaire**

The general health questionnaire (GHQ) is a self-administered screening questionnaire designed to use in consulting settings aimed at detecting those with a diagnosable psychiatric disorder. It is used for the detection of psychiatric distress related to general medical illness and frequently used as an indicator of psychological well-being. This latter construct resembles the psychological dimension of quality of life (Goldberg and Hillier, 1979; Kabuto et al., 1993).

It is available in a variety of versions using 12, 28, 30 or 60 items, but the 28-item version is used more widely. GHQ-28 contains four subscales: ‘somatic symptoms’, ‘anxiety and insomnia’, ‘social dysfunction’, and ‘severe depression’. Each item is accompanied by four possible responses, and the total possible score on the GHQ-28 ranges from 0 to 84. The higher the score, the poorer the psychological well-being of the subject has (Nagyova et al., 2000).

- **General noise sensitivity questionnaire**

Another questionnaire is for general noise sensitivity (GNS).Individuals can exhibit different annoyance reactions to the same noise, and these individual differences can be ascribed partly to differences in GNS. GNS was defined as “the internal states of any individual which increase their degree of reactivity to noise in general” (Job, 1999). A lot of researchers recognized the significance of GNS and agreed upon it as an intervening variable between noise exposure and annoyance, or considered GNS as a stable personality trait that individuals with high GNS had a predisposition to attend to noise and to perceive them negatively, so they showed stronger emotional reactions (Moreira and Bryan, 1972; Stansfeld, 1992). Some evidence states that 19% of the population is “more sensitive” than “average” and Stansfield concluded “the most potent predictor of noise annoyance, apart from the noise level, is noise sensitivity which is also associated with psychiatric disorder”. Taylor found that GNS could be the only personal background variable which had a significant effect on annoyance (Taylor, 1984). Likewise, Landon reported that GNS had a stronger impact on individual annoyance than noise level, which explained an additional 12 percent in reaction variance (Langdon, 1976). Investigation using mailed questionnaires was made with questions on self-reported noise sensitivity, attitudes to noise, annoyance due to environmental noises and the effect of noise on daily activities (Matsumura and Rylander, 1991). And it was found that GNS was more common in older age groups; noise-sensitive individuals were more annoyed by road traffic noise, and also reported interference with daily activities to a higher extent than non-sensitive persons, for example, listening to music during working or reading was less common in the noise-sensitive group. The study of traffic noise effects on mental performance got the results that annoyance while performing tasks under noisy conditions was regularly and significantly higher among subjects judged to have higher GNS on the Weinstein’s scale (Belojević et al., 1992). NS was had also influence on the decreased HRQOL (Health Related Quality of Life) through annoyance and sleep disruption (Shepherd et al., 2010), and on the annoyance level caused by indoor residential noises and outdoor traffic noise (Ryu and Jeon, 2011). Noise-sensitive people were also found less satisfied with their living environments (Nijland et al., 2007).

A physiological method to measure GNS is not available yet, because there is no theory specifying the relation between a physiological parameter and the answers to GNS questions. For the moment using questionnaires to determine the individual GNS is the feasible and widely used method. Questionnaires concerning experience, attitude and feelings toward noise were found to produce more discriminating sensitivity scores than did the single-item rating.

For example, the analysis result of the factorial structure of the “Fragebogen zur Erfassung der individuellen Lärmempfindlichkeit” (questionnaire for the assessment of the individual noise sensitivity) (Zimmer and Ellermeier, 1998) indicated that separate measurements for different areas of daily life might be more appropriate to determine the level of GNS. The “General Noise Sensitivity Questionnaire” (NoiSeQ) was developed to measure general noise sensitivity (GNS) as well as the sensitivity of five domains of daily life : *A-leisure, B-work, C-habitation, D-communication, E-sleep* in a German version (Schutte et al., 2007). The G-study analysis result showed that age, gender and time of measurement which were assumed to be potential sources of measurement errors, have no substantial effect on GNS. Therefore, the measurement of GNS could be restricted to one measurement for all age groups and for genders. And the reliability of this score met the demands of ISO 10075-3 for precision measurements. There are 35 items in the questionnaire, and a four-level rating scale (strongly agree=3, slightly agree=2, slightly disagree=1, and strongly disagree=0). The sum of the rating values of all items is calculated as the characteristic value for GNS, and a higher score indicates a higher sensitiveness to general noise.

- **LFN sensitivity questionnaire**

The questions chosen to classify whether people are sensitive to LFN (LFNS) are from two studies (Persson Waye et al., 2001) and (Pawlaczyk-Luszczynska et al., 2009). The reason of obtaining sensitivity for LFN was that people who were disturbed by LFN in their homes were found to develop a specific sensitivity to the noise sources, while they rarely considered themselves sensitive to noise in general (Persson Waye, 1995). Hence it is important to categorize subjects not only in terms of sensitivity to noise in general but also with respect specifically to LFN.

- **The Positive and Negative Affect Schedule (PANAS)**

PANAS is one of the most widely used scales to measure mood or emotion. It comprises two mood scales, one for positive affect and the other for negative affect with totally 20 items. High negative affect is epitomized by subjective distress and unpleasurable engagement, and low negative affect is the absence of these feelings. By contrast, positive affect represents the extent to which an individual experiences pleasurable engagement with the environment. Each item is rated on a 5-point scale ranging from 1 (very slightly or not at all) to 5 (extremely) to indicate the extent to which the subject has felt this way in the indicated time frame (Watson et al., 1988).

- **The Perceived Stress Scale (PSS)**

PSS is the most widely used psychological instrument for measuring the perception of stress. It measures which situations in one’s life are appraised as stressful. Items are designed to tap how unpredictable, uncontrollable, and overloaded subjects find their lives. PSS is not a diagnostic questionnaire, but it is proposed to make comparisons between individuals' perceived stress related to current, objective events. The higher the degree of PSS score indicates the higher risk factor for some disorders (Sheldon et al., 1983).

- **The Hearing problem self-test questionnaire (HP)**

HP is used commonly online for people's primary self-diagnosis whether they have normal hearing status. The subject only answers "Yes" or "No" to the questions, and the total score is the amount of "Yes".

The classification rules for all used questionnaires are in Table 2.1.1, which shows the critical value for each questionnaire and the represented meaning of different groups.

Table 2.1.1 The classification rules for the used questionnaires.

<table>
<tr><td rowspan="2">L/R handedness</td><td>L>R</td><td colspan="2">L<R</td><td>L=R</td></tr>
<tr><td>left-hander</td><td colspan="2">right-hander</td><td>both</td></tr>
<tr><td rowspan="2">GHQ</td><td colspan="2">≥ 24 <i>(GHQ-G1)</i></td><td colspan="2">< 24 <i>(GHQ-G2)</i></td></tr>
<tr><td colspan="2">poor mental performance</td><td colspan="2">normal mental performance</td></tr>
<tr><td rowspan="2">GNS</td><td>≥ 70 <i>(GNS-G1)</i></td><td colspan="2">> 70 ≥ 35 <i>(GNS-G2)</i></td><td>< 35 <i>(GNS-G3)</i></td></tr>
<tr><td>high GNS</td><td colspan="2">normal GNS</td><td>low GNS</td></tr>
<tr><td rowspan="2">LFNS</td><td colspan="2">≥ 13 <i>(LFNS-G1)</i></td><td colspan="2">< 13 <i>(LFNS-G2)</i></td></tr>
<tr><td colspan="2">sensitive to LFN</td><td colspan="2">not sensitive to LFN</td></tr>
<tr><td rowspan="2">PANAS</td><td colspan="2">(PA-NA) < 10 <i>(PANAS-G1)</i></td><td colspan="2">(PA-NA) ≥ 10 <i>(PANAS-G2)</i></td></tr>
<tr><td colspan="2">relative negative emotional situation</td><td colspan="2">relative positive emotional situation</td></tr>
<tr><td rowspan="2">PSS</td><td colspan="2">≥ 25 <i>(PSS-G1)</i></td><td colspan="2">< 25 <i>(PSS-G2)</i></td></tr>
<tr><td colspan="2">under high stress</td><td colspan="2">under normal stress</td></tr>
<tr><td rowspan="2">HP</td><td colspan="2">≥ 3 <i>(HP-G1)</i></td><td colspan="2">< 3 <i>(HP-G2)</i></td></tr>
<tr><td colspan="2">with slight hearing problem</td><td colspan="2">normal hearing status</td></tr>
</table>

2.2 Audio and video equipment

The experiments which operated in Germany were all taken in the same semi-anechoic chamber in the University of Wuppertal. The background noise level was 17 dBA. Figure 2.2.1 is the measurement result of the background noise. The 10 dB HL and 20 dB HL curves were the value of 10 dB and 20 dB higher than the average hearing threshold, which were used for the hearing threshold test in chapter 3.4. The level of the background noise in the low frequency range was lower than the hearing threshold, which meant that it would not affect the playback of the LFN signals in the tests.

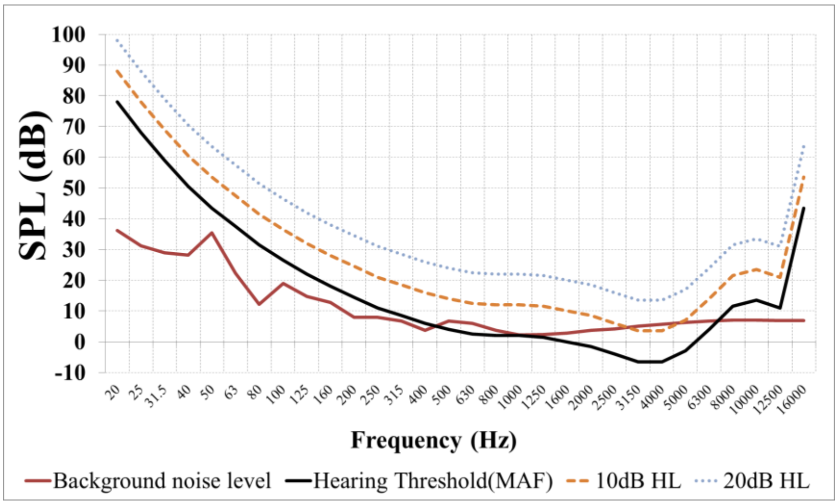


Figure 2.2.1 The spectrum measurement result of the background noise in the chamber

All the LFNs and involved low frequency PTs were replayed with the same loudspeaker - Neumann KH870. The frequency range of this loudspeaker is 18 Hz to 300 Hz with THD <0.001% (Figure 2.2.2, in the left graph the green curve is the frequency response, and the right graph is the THD measurement result). The loudspeaker to present pink noise and other higher frequency sounds is the loudspeaker - Neumann KH120. The frequency range of this loudspeaker is 52 Hz to 20 KHz with THD <0.1% (Figure 2.2.3, left is the frequency response, and right is THD). The visual material involved in the thesis was taken with a camera - Canon EOS 700D m.

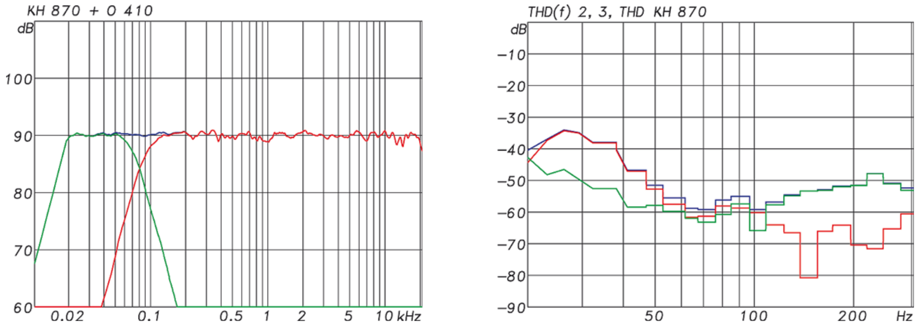


Figure 2.2.2 The frequency response (left, green line) and THD (right) of Neumann KH870 (http://www.neumann-kh-line.com/)

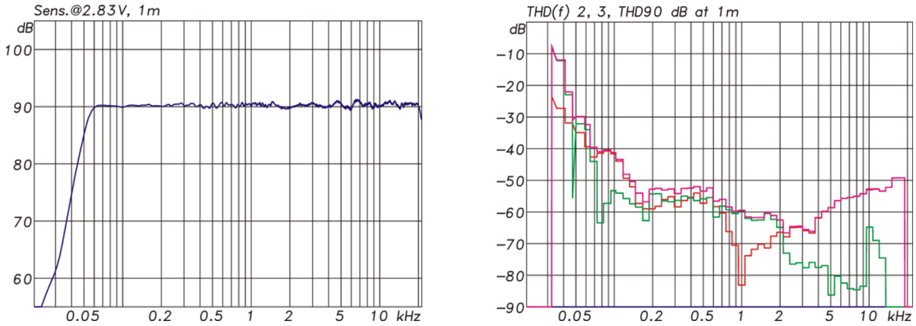


Figure 2.2.3 The frequency response (left) and THD (right) of Neumann KH120 (http://www.neumann-kh-line.com/)

2.3 Devices and operating process for EEG measurement

2.3.1 EEG devices and the 10-20 system

There were three EEG devices used in the studies (Figure 2.3.1). BIOPAC MP150 is a multiple research workstation, which can obtain not only EEG signals, but also EOG, ECG etc. It can be extended to 16 channels, but only one electrode channel and the reference channel were used here. The Emotiv EPOC Headset is a wireless EEG system with 14 EEG fixed channels on the basis of 10-20 system. The main EEG equipment is the Neuron-Spectrum-5, which has the possibility of recording any 32 monopolar derivations of 10-10 system and 4 wideband channels for the EOG recording. The same EEG cap for all EEG measurements was from EASYCAP in three sizes. The ring electrodes made with sensors of high-purity sintered Ag/AgCl were used to connect between the cap and the BIOPAC MP150 or Neuron-Spectrum-5 with a 1.5 mm touch proof safety socket.

Figure 2.3.1 EEG devices - BIOPAC MP150 (L), Emotiv EPOC Headset (M) and Neuron-Spectrum-5 (R)

(https://www.waisman.wisc.edu/ImagingCore-eeg.htm), (https://emotiv.com/), (http://neurosoft.com/en)

The 10-20 System is an internationally recognized method to describe and apply the location of scalp electrodes in the context of an EEG device, which is recommended by the International Federation of Societies for EEG and Clinical Neurophysiology in 1958 (Jasper, 1958). This system is developed to gain consistency between laboratories, which is based on the relationship between the location of an electrode and the underlying area of the cerebral cortex. The head is divided into proportional distances from prominent skull landmarks (nasion, preauricular points and inion) to provide adequate coverage of all regions of the brain. The numbers '10' and '20' refer to the fact that the distances between adjacent electrodes are either 10% or 20% of the total front-back or right-left distance of the skull. Each site has a letter to identify the lobe and a number to identify the hemisphere location (Table 2.3.1). The 10-10 system is proposed due to the advent of multi-channel EEG hardware systems, the concurrent development of topographic methods and tomographic signal source localization methods. It is an extension of the original 10-20 system with a higher channel density of 81 (Chatrian et al., 1985). There are several classifications for the boundary frequencies of each EEG band (Larsen, 2011; Ochoa, 2002; Solomon, 1983; Thomas F. Collura, 1997). Table 2.3.2 lists the boundary frequencies of the rhythm used in this thesis.

Table 2.3.1 The meanings and functions of the letter and number for electrode positions in 10/20 system.

Electrode	**Lobe**	**Function**
F	Frontal	associated with reasoning, planning, parts of speech, movement, emotions and problem solving
T	Temporal	associated with perception and recognition of auditory stimuli, memory and speech
P	Parietal	associated with movement, orientation, recognition, perception of stimuli
O	Occipital	visual sensation and processing
C	Central*	(No central lobe exists; 'C' is used for identification purposes only)
Other explanations		
The 'z' (zero) refers to an electrode placed on the mid line	Even numbers (2,4,6,8) refer to electrode positions on the right hemisphere	Odd numbers (1,3,5,7) refer to electrode positions on the left hemisphere

The monopolar montage (referential montage) recording method was chosen to be used for the EEG measurements, which was widely used in scientific research. The potential of each electrode was compared to a reference electrode. Cz was the used reference position with an advantage that Cz was located in the middle among active electrodes. Because for the modern instrumentation the choice of a ground electrode played no significant role in the measurement, forehead (FPz) was chosen as the ground electrode. Considering the aim of the study, the cortex areas related to auditory, visual and emotional perceptions were chosen. Table 2.3.3

shows lists of the involved electrode positions. Figure 2.3.2 is the graph of the selected electrodes and the Brodmann area positions displayed in 10-10 system.

Table 2.3.2 The boundary frequencies of the used EEG bands.

Rhythm	**Frequency range**	**Rhythm**	**Frequency range**
Theta (θ)	[4Hz, 8Hz)	Theta1 (θ1)	[3.5Hz, 5.4Hz]
		Theta2 (θ2)	[5.4Hz, 7.4Hz]
Alpha (α)	[8Hz, 13Hz]	Alpha1 (α1)	[7.4Hz, 9.9Hz]
		Alpha2 (α2)	[9.9Hz, 12.4Hz]
Beta (β)	(13Hz,30Hz]	Beta1 (β1)	[12.5Hz, 18Hz)
		Beta2 (β2)	[18Hz, 24Hz)
		Beta3 (β3)	[24Hz, 30Hz]

Table 2.3.3 The selected electrode postions and the corresponding Brodmann areas functions.

Electrode position	**Lobe area**	**Brodmann area**	**Function**
FP1, FP2	Frontal lobe	10	processing emotional stimuli
AF3, AF4		9	
AFz			
Fz		8	Auditory imagery selective attention
F3, F4			
F7		47	adverse emotional inhibition
F8		45	eomtional processing
C3	central electrodes	2	sensory functions short term memory
C4		1	
C5		42	basic processing of auditory stimuli
C6		41	
FCz		6	selective to sounds
FC3, FC4			
FC5, FC6		44	music enjoyment
T3	Temporal lobe	42	basic processing of auditory stimuli
T4		21	processing complex sounds
TP7, TP8			
T5, T6		37	emotional content
O1, O2	Occipital lobe	18	visual processing
Oz		17	response to emotion/attention in visual processing
P3, P4	Parietal lobe	39	spatial focusing of attention
Pz		7	visuosoatial processing

2.3.2 The operating process for EEG measurement

Generally the first stage of an EEG observation or measurement was the preparations for the subjects, which included notifying them of the relevant requirements, asking their basic health situation and presenting them the measurement information. In detail, the subjects were asked whether they were taking any medicines, such as sedatives and tranquilizers, muscle relaxants, sleeping aids, or medicines used to treat seizures. And they were told not to eat or drink, food contained caffeine (such as coffee, tea, cola, and chocolate) at least 4 hours before the measurement. For a good attachment between electrodes and the scalp, the subjects should make sure that their hairs were clean and free of sprays, oils, creams, and lotions. So they were asked to wash and rinse their hair with clear water the evening before or the morning of the test, and not put any hair conditioner or oil on after shampooing. The EEG cap was selected depending on the size of the subject's head.

When all electrodes were connected to the cap, the impedance was checked, which was the index for a good contact of the EEG electrodes to the scalp. The lower the impedance meant the smaller interfering noise and better contact. Impedances with a value lower than 10 KΩ were accepted. The sample frequency was set to 200 Hz, which was higher than the frequency range of the analyzed EEG bands. The format to save EEG data was the European Data Format (EDF), which was a simple and flexible format for exchange and storage of multichannel biological and physical signals. Then the subjects were asked to do the required operation while their EEG was recorded. For example, they were asked to close their eyes, sit still and relax in the chair, and avoid large body movement when there was only auditory stimulus in the test. And when there were both auditory and visual stimuli involved, the subjects were asked to focus their sight on the screen and avoid large head and body movements. After the EEG measurement the data were analyzed with the software to reject the artifacts and deal with other methods to get clean EEG data.

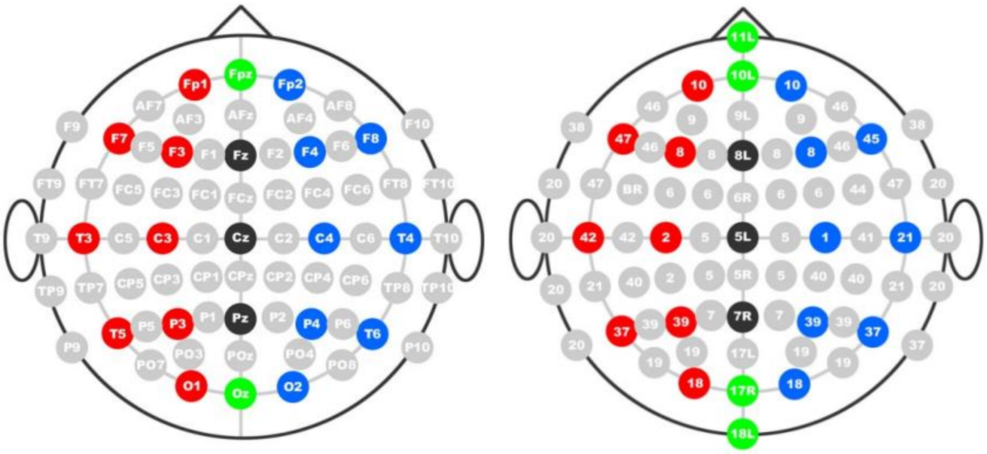


Figure 2.3.2 The electrode positions and the Brodmann area in 10-10 system(Chai, 2012)

2.4 EEG analysis methods and software

2.4.1 Artifacts during EEG measurement

EEG electrodes do not only collect the EEG signals, but also obtain all kinds of electromagnetic pollution. Signals that are detected by an EEG device, but do not belong to the cerebral origin are called artifacts (Núñez, 2010). They may occur at many points during the recording process and can be classified into three main categories: 1) biologic (arising from the subjects), 2) technologic (arising from the electrode-subject interface, electrodes, electrode connections, recording equipment or display apparatus) and 3) extrinsic (such as main line interference; other equipment connected to the subjects; airborne sources, including electromagnetic, radio frequency, and electrostatic signals; and other environmental phenomena) (Klass, 1995). Figure 2.4.1 contains a sample of clean EEG signal and the commonly appeared types of the EEG artifacts (Dhiman et al., 2010).

- **Eye blink and eyeball movement artifacts**

The eye blink artifact is attributed to alterations in conductance arising from the contact of the eyelid with the cornea. An eye blink can last from 200 to 400 ms and can have an electrical magnitude more than 10 times that of cortical signals, and corrupt data on all electrodes, even those at the back of the head. The other type artifact is the eyeball movement artifact. The eyeball can be regarded as a dipole with positivity toward the cornea and negativity toward the retina. When the eyeball is in a fixed position, the dipole does not yield any potential change in the EEG. But when the eyeball moves, this moving dipole generates a large AC potential detected by electrodes near the eyeballs.

- **Power line artifact**

The source of the most significant noise is acquired from the power line introducing electromagnetic signals of 50 Hz. A notch filter is used to reject this low frequency line noise and harmonics.

- **Muscle artifact**

These artifacts are caused by activities in different muscle groups including neck and facial muscles. They are in high frequency range and can be readily identified because of their outlying high values relative to the EEG signals.

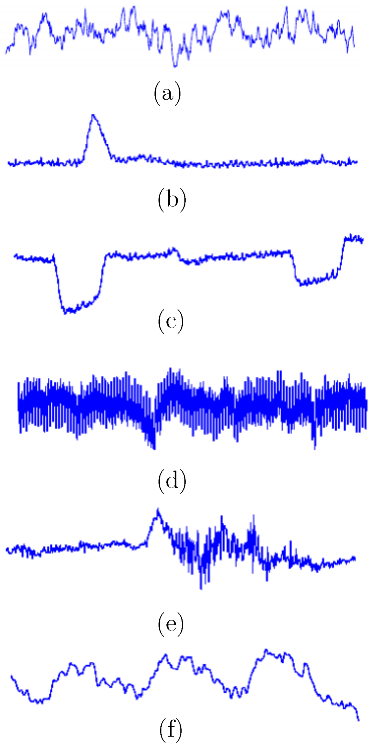


Figure 2.4.1 The samples of clean EEG signal and artifacts (a) Clean EEG, (b) Eye blink, (c) Eye movement, (d) 50Hz, (e) Muscle activity, (f) Pulse (Dhiman et al., 2010)

- **Pulse artifact**

When an electrode is placed on or near a blood vessel it could record pulse or heart beat artifacts, which have a frequency around 1.2 Hz.

2.4.2 Software and method to obtain clean EEG data

The software used to find and reject artifacts from EEG data was EEGLAB, which is an interactive Matlab toolbox for processing continuous and event-related EEG, MEG and other electrophysiological data incorporating Independent Component Analysis (ICA), time/frequency analysis, artifact rejection, event-related statistics, and several useful modes of visualization of the averaged and single-trial data (EEGLAB - http://sccn.ucsd.edu/eeglab/).

As a non-invasive method, EEG obtained from scalp electrodes is the sum of a large number of neuron potentials, which globally describe the brain activity. The displayed signals are sums of the neurons activity with weights, which are depended on the signal path from the brain cell to the electrodes. And because the same potential is recorded by several nearby electrodes, the signals from these electrodes are found to be highly correlated. The hypothesis is that if the weight is known, the potentials in the sources inside the brain could be calculated from a sufficient number of electrode signals. ICA as a method of decomposing a set of multivariate data into its underlying statistically independent components is proven useful to solve the weights problem and most often to detect and remove artifacts (Jung et al., 2000, 1998; M. Ungureanu et al., 2004; Makeig et al., 1996). As in left graph in the Figure 2.4.2, ICA finds an unmixing matrix -“W” which linearly decomposes the multichannel EEG data -“x” into a sum of maximally temporally independent and spatially fixed components. The projection strengths of the respective components onto the scalp sensors are given by the columns of the inverse matrix W^{-1}. Different biological performances are shown from the scalp topographies of the ICs. And then as shown in the right graph, the ICs responsible for artifacts are set to zero and all other ICs can be projected back onto the scalp EEG data.

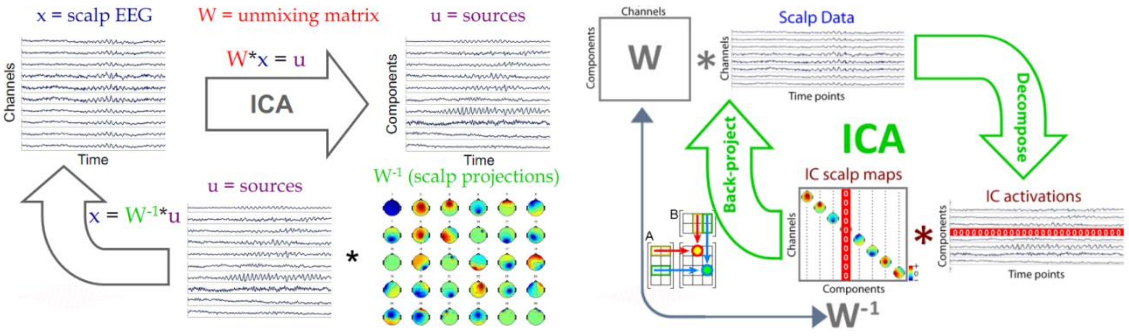


Figure 2.4.2 The principle of ICA for EEG data in EEGLAB (Julie Onton, 2010)

The procedure to get clean EEG data was summarized as follows (Julie Onton, 2010):

1) Divide EEG data into segments with the length reference to the auditory stimuli;

2) Confirm the location of all electrodes relative to the reference position Cz;

3) Reject large muscle artifacts or otherwise strange events, but keep stereotyped artifacts (like eye blink);

4) Run ICA, review component properties and identify the artifacts; (Figure 2.4.3 shows different kinds of artifact examples appeared in the thesis)

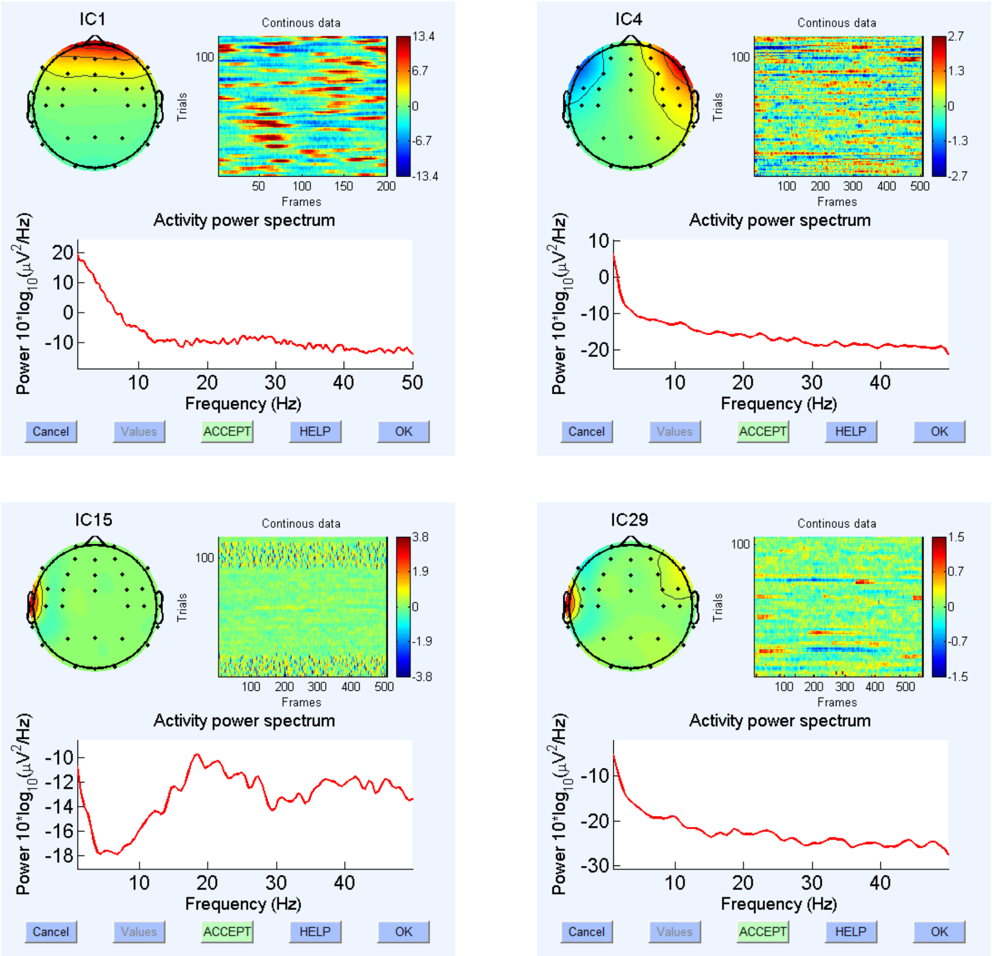


Figure 2.4.3 The artifact ICs examples (IC1- Eye blink component, IC4 - Lateral eye movement; IC15 - Muscle movement; IC29 - Bad channel)

5) Remove the artifact ICs.

6) Save the clean EEG data in EDF format.

After obtaining clean EEG data the power spectral density (PSD) was calculated with the Neuron-Spectrum software for different EEG bands. PSD shows how the strength of a signal is distributed over the frequency domain and its unit is energy per frequency (Samaneh Valipour and Shaligram, 2014). In other words, PSD demonstrates the strength of the variations in energy of a signal as a function of frequency. Therefore, the incorporating PSD of specific EEG frequency ranges could represent the energy variations.

3 Subjective evaluation listening tests and EEG measurements

The purpose of this chapter was to use different measuring methods to find out whether subjects with different personality traits could have different perceptions and reactions on LFN in subjective and objective aspects, especially observing the differences between LFN sufferers and the reference subjects. The subjective evaluation listening test was a common method to directly obtain the strength of feelings caused by LFN. The objective method to observe the effect caused by LFN, or more specifically the brain reaction due to LFN was the EEG measurement. There were totally five experiments included with different aims. The specific experiment materials, methods, processes and data analyses for the listening tests and EEG measurements were described separately.

3.1 The indirect method test

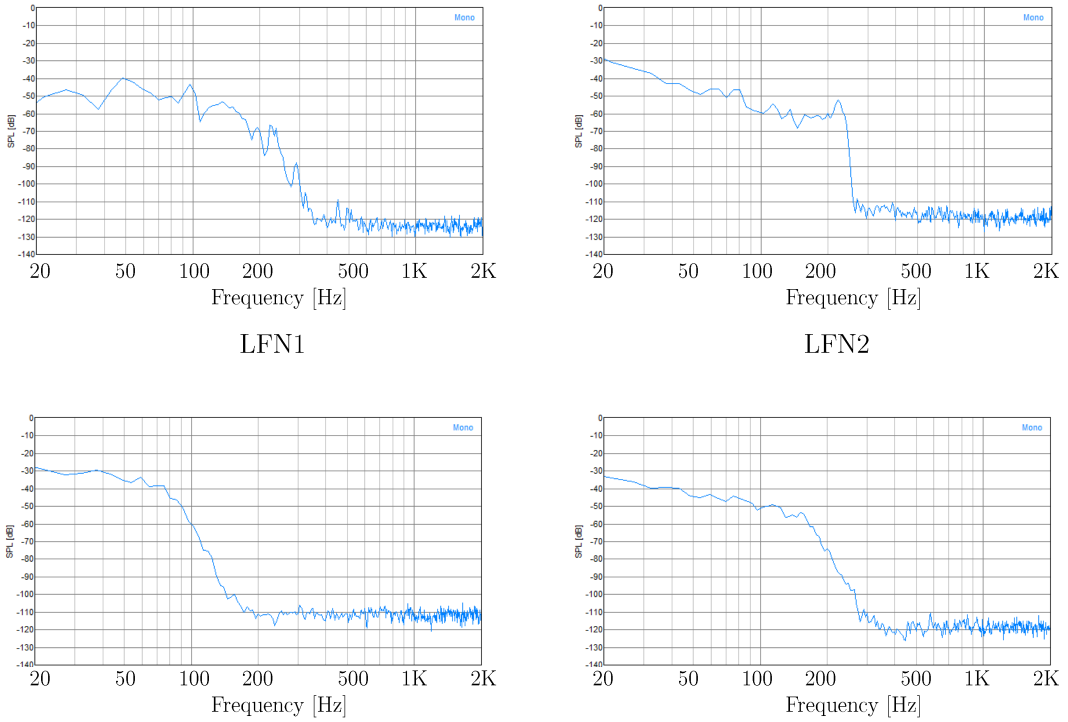
One purpose of this test was to investigate the subjective perception and reaction on LFN for normal subjects, who didn't match as LFN sufferers but had different general noise sensitivities (GNS). The other purpose was to demonstrate the feasibility of the indirect method (sound adjustment) that using extra sounds in middle or high frequency range could reduce the annoyance caused by LFN, and to find out the specific additional components which were suitable to use for subject with different GNS.

3.1.1 Subjects and experiment conditions

Sixteen students (5 males and 11 females) with a normal self-reported hearing situation from the Capital Normal University of China (首都师范大学) were recruited as subjects in the experiment. The age of the subjects was 20 or 21, and they were not LFN sufferers. The experiment was made in a regular classroom and the playback equipment was a full band loudspeaker.

3.1.2 Experimental signals and method

There were four original LFN signals. LFN1 was recorded from a heat pump unit in the center of an office in China (Di et al., 2011), which had a main energy lower than 250 Hz. LFN2 was recorded in an apartment whose owner suffered from LFN in Germany. LFN3 and LFN4 were generated from software. LFN3 (BN-80 Hz) was the Braun Noise through a Butterworth low pass filter with the cut-off frequency at 80 Hz and the order at 10, and LFN4 (BN-160 Hz) was obtained with the same filter and order but with 160 Hz as the cut-off frequency. The SPL of all original LFNs was 45 dBA. Figure 3.1.1 is the power spectrum information about the original LFN in frequency range of 20 - 2000 Hz with relative SPL.



LFN1

LFN2

LFN3

LFN4

Figure 3.1.1 The power spectrum of four original LFN signals

The signals as the additional components to combine with LFN were bandwidth pink noise (PN) and white noise (WN), which were obtained from ArtemiS 12.0 (HEAD acoustics GmbH). The SPLs of these signals were 15 dB, 20 dB and 25 dB, and the frequency ranges are listed in Table 3.1.1. LFN1 and LFN4 were combined with both PN and WN, LFN2 and LFN3 were only combined with PN as the additional components. So, totally there were six independent sub-tests (Table 3.1.2). A previous study suggested that 5 s was an appropriate duration of sound exposure to obtain the subjective evaluation (Otto et al., 2001). Therefore, the duration of each noise sample was 5 s, with an interval of 3 s.

Table 3.1.1 The bandwidth frequency ranges of the additional PN and WN.

250 Hz - 500 Hz	250 Hz - 4K Hz	1K Hz - 2K Hz
250 Hz - 1K Hz	500 Hz - 1K Hz	2K Hz - 4K Hz
250 Hz - 2K Hz	500 Hz - 2K Hz	4K Hz - 8K Hz

Table 3.1.2 The information of the six-subtests in experiment 3.1.

Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
LFN1 + PN	LFN1 + WN	LFN2 + PN	LFN3 + PN	LFN4 + PN	LFN4 + WN

The subjects answered GNS questionnaire before the listening test. The magnitude estimation method was adopted as the subjective evaluation method. There were seven annoyance levels (from 1 to 7), from 1 as the lowest up to 7 as the highest. The SAV of each original LFN was set to 4 in every sub-test and always played as the first signal with a given SAV on the test tables. In each sub-test there were 36 stimuli in a random order, which included LFN combined with PN or WN (27 stimuli) and 9 repetitions of the original LFN. Because the SAV of the original LFN in each sub-test was given as “4”, the SAV of the other repeated LFN was also supposed as “4”. Then the amount of annoyance evaluation of LFN for “4” was counted as the reliability for each subject. At the end of the whole listening test, subjects were asked whether they had a headache, earache, or any other physiological and psychological negative feelings.

3.1.3 Data analysis

Table 3.1.3 is the summarized information and questionnaire results of all subjects. Besides headache and earache, some subjects reported feelings of nausea, dizziness and dysphoria.

Table 3.1.3 The information of subjects and questionnaire results (classification rules are Table 2.1.1; in GNS questionnaire: A-leisure, B-work, C-habitation, D-communication and E-sleep).

Subjects	**Age**	**Gender**	**General Noise Sensitivity**						**GNS groups**	**Headache**	**Earache**
			Sum	**A**	**B**	**C**	**D**	**E**			
P1	21	F	57	13	9	10	12	13	G2	Yes	Yes
P2	20	F	63	11	10	13	15	14	G2	No	No
P3	20	M	55	12	9	12	13	9	G2	No	Yes
P4	20	M	61	8	15	16	13	9	G2	Yes	Yes
P5	20	F	54	12	12	10	12	8	G2	No	No
P6	20	F	87	18	15	18	17	19	G1	Yes	Yes
P7	20	F	70	12	13	15	14	16	G1	Yes	Yes
P8	20	F	64	11	11	11	13	18	G2	No	Yes
P9	21	F	64	17	13	12	13	9	G2	No	No
P10	20	F	71	15	10	17	11	18	G1	Yes	Yes
P11	20	F	65	9	12	14	11	19	G2	No	No
P12	20	M	64	14	16	12	13	9	G2	No	Yes
P13	20	M	53	14	13	8	13	5	G2	Yes	No
P14	21	M	63	14	10	14	11	14	G2	No	No
P15	21	F	90	19	18	17	16	20	G1	Yes	Yes
P16	20	F	65	15	14	12	15	9	G2	Yes	Yes

The average subjective annoyance value (SAV) of the subjects who passed the reliability test were calculated and summarized for six sub-tests (Appendix 2). To check whether the SAV of LFN combined with PN or WN could decrease due to the additional components, the combinations with SAV lower than “4” which meant that these signals caused lower annoyance level than the original LFN were summarized for GNS-G1 and GNS-G2 to compare the different perceptions and reactions between subjects with high and normal GNS (Table 3.1.4). The results showed a trend that only PN as the additional component to combine with LFN could reduce the annoyance for GNS-G1, whereas for GNS-G2 adding either PN or WN with LFN had an annoyance reduction effect.

Table 3.1.4 The combination with SAV (range from 1 to 7) < 4 for GNS groups.

Combination for GNS-G1	**SAV**
LFN1-PN-250-500Hz-15dB	3.75
LFN1-PN-500-2KHz-15dB	3.5
LFN1-PN-250-1KHz-20dB	3.75
LFN1-PN-250-2KHz-20dB	3.75
LFN1-PN-250-4KHz-20dB	3.75
LFN1-PN-250-500Hz-25dB	3.5
LFN1-PN-2K-4KHz-25dB	3.25
LFN2-PN-250-1KHz-20dB	3.63
LFN2-PN-250-2KHz-20dB	3.88
LFN2-PN-2K-4KHz-20dB	3.75
LFN3-PN-500-1KHz-15dB	3.67
LFN3-PN-250-4KHz-20dB	3.67
LFN3-PN-250-1KHz-25dB	3.67
LFN4-PN-4K-8KHz-20dB	3.67
LFN4-PN-250-4KHz-25dB	3.67
LFN4-PN-1K-2KHz-25dB	3.67

Combination for GNS-G2	**SAV**
LFN1-PN-500-2KHz-15dB	3.6
LFN1-PN-250-500Hz-25dB	3.8
LFN1-PN-250-1KHz-25dB	3.8
LFN1-WN-250-1KHz-15dB	3.83
LFN1-WN-250-2KHz-20dB	3.83
LFN1-WN-250-1KHz-25dB	3.91
LFN2-PN-250-1KHz-20dB	3.75
LFN2-PN-250-2KHz-20dB	3.75
LFN4-PN-2K-4KHz-20dB	3.82
LFN4-PN-4K-8KHz-20dB	3.91
LFN4-WN-250-500Hz-15dB	3.91
LFN4-WN-250-1KHz-20dB	3.91
LFN4-WN-250-2KHz-20dB	3.73
LFN4-WN-250-4KHz-20dB	3.82
LFN4-WN-500-1KHz-20dB	3.64
LFN4-WN-250-500Hz-25dB	3.91

Table 3.1.5 is the SAV results of four LFN signals combined with PN or WN in three levels for two GNS groups. It showed that the SAV of GNS-G1 was lower than that of GNS-G2, when the additional component was bandwidth PN. And the result was opposite with bandwidth WN as the additional component, the SAV of GNS-G1 was higher. The only exception was for LFN4 combined with PN in 20 dB. This sub-test was the last one and the subjects were tired, which could cause the inconsistent result. This result indicated that there could be different suitable noise types as the additional components for subjects with different GNS to use the indirect method to reduce the annoyance caused by LFN, and adding PN with original LFN could get a better result than adding WN for subjects with high GNS. Figure 3.1.2 gives the results of LFN1 combined with PN in 15 dB, 20 dB and 25 dB.

Table 3.1.5 The SAV (range from 1 to 7) results of LFN signals combined with PN or WN in three levels for two GNS groups.

	LFN1		LFN2		LFN3		LFN4	
	GNS-G1	GNS-G2	GNS-G1	GNS-G2	GNS-G1	GNS-G2	GNS-G1	GNS-G2
PN-15dB	**4.25**	4.58	**4.42**	4.77	**4.07**	4.71	**4.33**	4.34
WN-15dB	4.56	**4.31**					4.72	**4.31**
PN-20dB	**4.11**	4.50	**4.03**	4.36	**4.07**	4.63	4.37	**4.30**
WN-20dB	4.61	**4.39**					4.33	**4.05**
PN-25dB	**4.17**	4.37	**4.53**	4.93	**4.56**	4.71	**4.30**	4.39
WN-25dB	5.08	**4.43**					4.69	**4.40**

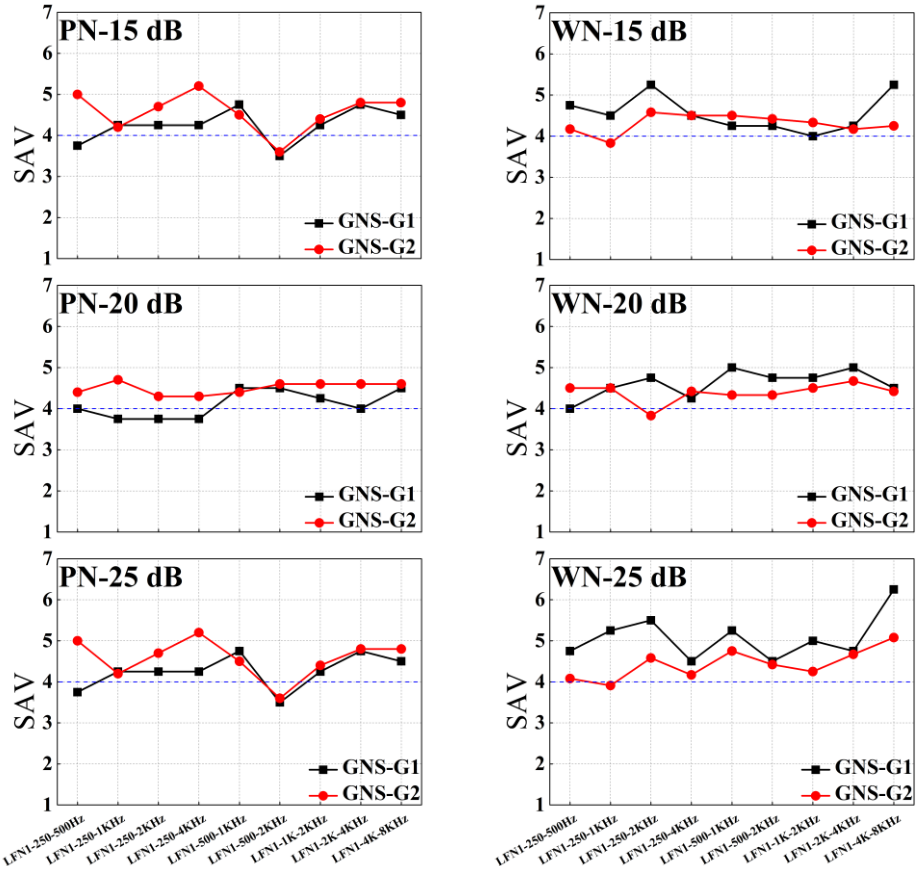


Figure 3.1.2 The SAV results for LFN1 combined with PN or WN in three levels

(X axis - LFN1 combined with PN (left) or WN (right) in different frequency ranges; Y axis - SAV (range from 1 to 7))

The Paired-Sample T Test was used to check the significant different evaluations between LFN combined with PN and with WN for LFN1 and LFN4. Table 3.1.6 is the summarized result and a *p*-value smaller than 0.05, which means significant, is emphasized in blue. For GNS-G1 the significant differences were found for LFN1 combined with PN and with WN in 20 dB and 25 dB, and for LFN4 with additional components they were at 15 dB and 25 dB. It indicated that subjects with high GNS had obvious different perceptions and reactions on LFN combined with different components. In the meanwhile, there was no significant different SAV result caused by two kinds of components added with original LFN for GNS-G2. There were significant results for gender, and for female and male subjects the differences were found for different situations.

Table 3.1.6 The Paired-Sample T Test results (*p* value) for the comparison between LFN combined with PN and with WN.

	LFN1			LFN4		
	15dB	20dB	25dB	15dB	20dB	25dB
Average	.426	.305	.127	.428	.271	.185
GNS-Group1	.171	**.004**	**.003**	**.009**	.843	**.049**
GNS-Group2	.144	.123	.697	.787	.186	.901
Male	**.027**	.360	.420	.244	.343	**.005**
Female	.882	.204	**.017**	1.000	.302	.244

Figure 3.1.3 is the SAV results of LFN1 combined with PN and with WN in 20 dB, which support the Paired-Sample T Test results. The SAVs of LFN1 combined with PN and combined with WN were almost the same for GNS-G2, but for GNS-G1 the SAVs of LFN1 combined with PN were significantly lower than the SAVs of LFN1 combined with WN.

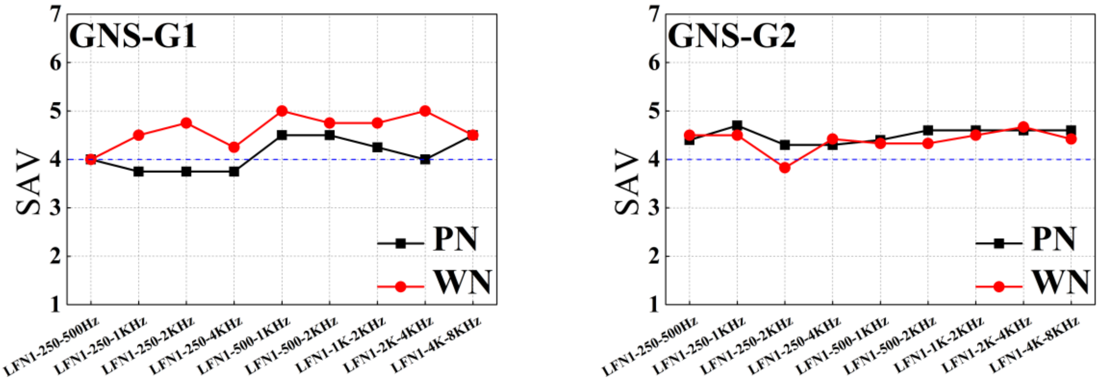


Figure 3.1.3 The SAV comparison results of LFN1 combined with PN (20dB) and with WN (20dB) between two GNS groups
(X axis - LFN1 combined with PN or WN in different frequency ranges; Y axis - SAV (1-7))

Then the difference among three SPLs of the additional PN or WN was checked also for two GNS groups and for genders. Firstly One-Way ANOVA was run in SPSS, but some data didn't pass the Homogeneity of variances test, which was the basic requirement for using One-Way ANOVA to determine whether there was any significant difference between the means of two or more independent (unrelated) groups. So the Kruskal-Wallis H test as a rank-based nonparametric test was used instead when the data didn't pass the Homogeneity of variances test, which was run for sub-test 1 and 3. Table 3.1.7 shows the calculation results of six sub-tests. The results showed that the different SPLs of the additional PN or WN didn't have strong influence on all subjects in the six sub-tests, but there were significant results in 4 sub-tests for GNS-G1, which meant that for subjects with high GNS the level of additional components could cause obvious different annoyance reactions.

Table 3.1.7 The results of One-Way ANOVA and Kruskal-Wallis H test for the comparison between different levels of the additional PN or WN.

Sub-test		**SPSS results**	**All**	**GNS-G1**	**GNS-G2**	**Female**	**Male**
1	LFN1+PN	Chi-Square	1.628	.631	1.463	2.769	2.895
		Asymp. Sig.	.443	.729	.481	.250	.235
2	LFN1+WN	F	1.695	3.643	.469	1.466	.778
		Sig.	.205	**.042**	.631	.251	.471
3	LFN2+PN	Chi-Square	6.294	8.264	4.788	4.316	5.848
		Asymp. Sig.	**.043**	**.016**	.091	.116	.054
4	LFN3+PN	F	1.064	7.179	.242	.092	1.898
		Sig.	.361	**.004**	.787	.912	.172
5	LFN4+PN	F	.137	.082	.351	.160	.961
		Sig.	.873	.921	.708	.853	.397
6	LFN4+WN	F	5.475	4.231	3.716	6.591	1.132
		Sig.	**.011**	**.027**	**.039**	**.005**	.339

All the obtained results proved the feasibility of the indirect method that using additional components could reduce the annoyance caused by LFN. And in the list of the combinations which had a lower annoyance level than that of the original LFN, PN or WN in the middle frequency ranges, such as 250-500Hz, 250-1KHz, and 500-1 KHz, which overlapped the energy falling frequency range of the original LFN, they took a high proportion. For subjects with high GNS, the annoyance was only found decreased when PN was the additional component combined with the original LFN. And for subjects with normal GNS, adding PN or WN with LFN could both reduce the annoyance. This finding was agreed with the Paired-Sample T Test result. The significant comparison result between LFN combined with PN and with WN was found for GNS-G1 but not for GNS-G2. Different SPLs of PN or WN didn't show statistically significant influence on GNS-G2, the effect was mostly found for GNS-G1. These findings suggested that when trying to perform the indirect method to reduce the negative effects caused by LFN, it was necessary to measure the GNS of the subjects first. When they were with high GNS, PN could be considered as the additional component to combine with LFN and the SPL of it needed to be tested. No significant gender difference was found in this listening test, however, the 4 subjects with higher GNS were all females.

3.2 The different brain reactions to LFN and PN

This was a pilot EEG test so the amount of subjects and EEG electrodes were small. The aim was to prove the hypotheses that different noise exposures could cause obvious different brain reactions, and EEG was a useful tool to observe the variations.

3.2.1 Subjects and experiment procedure

There were three male subjects joined in this test. They answered GNS, GHQ and PANAS questionnaires before the EEG measurement. There were two noise signals - LFN and pink noise (PN). LFN was the Brown noise through the Butterworth low pass filter with a cut-off frequency at 125Hz and the order at 10. PN was also generated from Audition 3.0 with a frequency range from 20 Hz to 20000 Hz. Steady PN was demonstrated that it had a significant effect on reducing brain wave complexity and induced more stable sleep time to improve sleep quality of individuals (Zhou et al., 2012). Both stimuli were set to 50 dBA. Figure 3.2.1 is the power spectrum of LFN and PN with relative SPL.

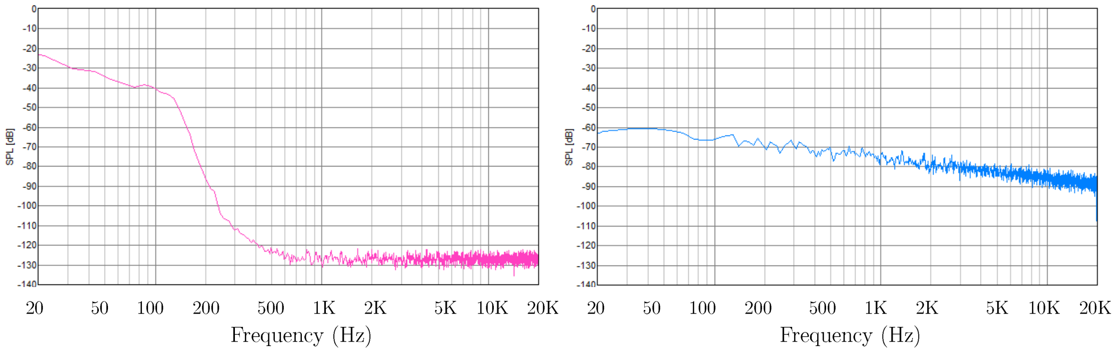


Figure 3.2.1 The power spectrum of LFN (left) and PN (right)

According to the earlier result, the exposure duration of the noise should not be too short, otherwise the EEG variation would be irregular from receiving noise to making stress responses (Li et al., 2014). So the duration of the noise signals was 5 minutes during the EEG measurement. Subjects sat in front of the loudspeaker with a 1.5 m distance, and were asked to keep still with their eyes closed during the whole EEG measurement. The procedure of the test is shown as in Figure 3.2.2. After that they needed to give their annoyance judgements about LFN and PN, and the more annoying one had a higher subjective annoying value. The EEG device was BIOPAC MP150, and the chosen electrode position was T4.

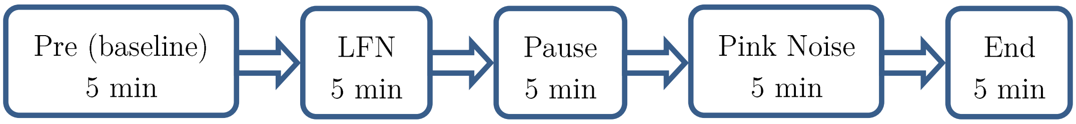


Figure 3.2.2 The process of the pilot EEG test

3.2.2 Data analysis

Table 3.2.1 summarizes the results, which include the basic information about the subjects, the results of the questionnaires, and the annoyance relation between two signals. It was found that the scores of GHQ and PANAS were mostly the same among subjects, and the differences were their GNS and annoyance evaluation results.

Table 3.2.1 The summarized questionnaire and annoyance evaluation results (classification rules are Table 2.2.1).

Subject	Age	General Noise Sensitivity (GNS)		GHQ	PANAS		annoyance level
					PA	NA	
P1	30	79	GNS-G1	35	23	25	LFN>PN
P2	27	64	GNS-G2	33	22	25	LFN≈PN
P3	31	48	GNS-G2	35	25	20	LFN<PN

After rejecting the artifacts, the power spectral density (PSD) of the clean EEG data was calculated for each segment. Considering the individual difference of the EEG level, the relative PSD (RPSD) was calculated as the index, which was the ratio of the PSD in each segment to the reference PSD. The reference PSD was the average PSD value of the baseline segment. Figure 3.2.3 is the RPSD result for each subject. There were two aspects obtained from the average RPSD results. One was that the brain reactions to LFN and PN were different for each subject, for example, the RPSD of α1, α2, β, β2 and θ showed distinct differences for all subjects. The other aspect was that there were obvious differences among the three subjects that the amplitude of most RPSD values for P1 was positive, but for P2 and P3 the values were almost negative, which might be due to the different GNS level. Table 3.2.2 is the comparison of evaluated annoyance value and PSD for 10 EEG bands between LFN and PN.

Table 3.2.2 The relationship between LFN and PN by EEG bands (LFN – “L”, PN – “P”).

	annoyance	α	α1	α2	β	β1	β2	β3	θ	θ1	θ2
P1	L>P	L<P	L>P	L<P	L<P	L>P	L<P	L>P	L<P	L>P	L<P
P2	L≈P	L>P	L>P	L>P	L<P	L<P	L<P	L=P	L>P	L=P	L=P
P3	L<P	L>P	L>P	L>P	L>P	L>P	L>P	L>P	L<P	L>P	L>P

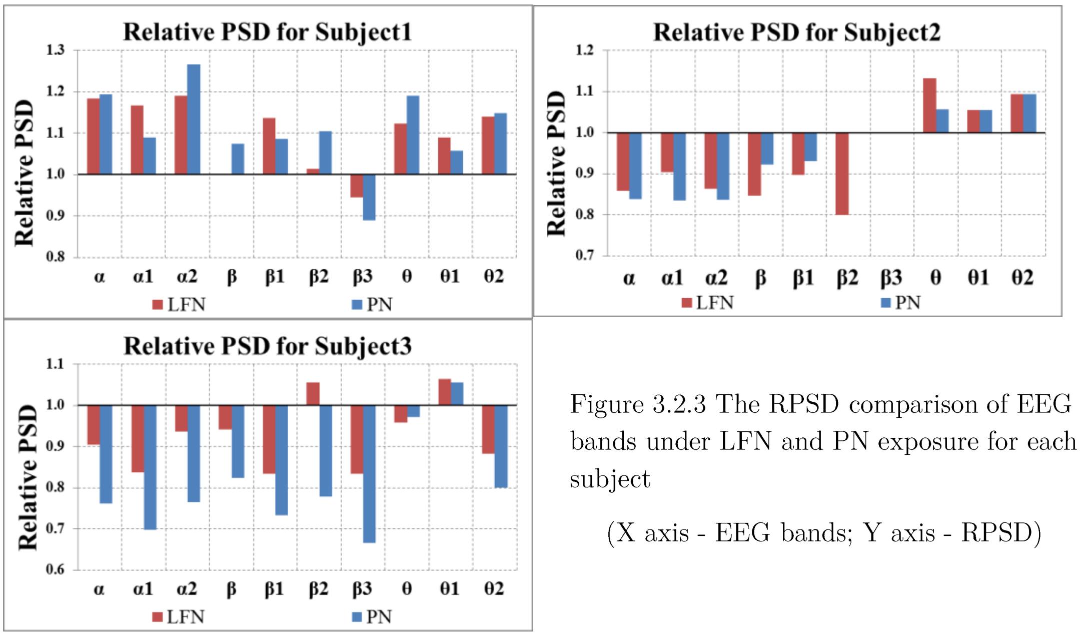


Figure 3.2.3 The RPSD comparison of EEG bands under LFN and PN exposure for each subject

(X axis - EEG bands; Y axis - RPSD)

The variations of PSD over time under LFN and PN exposure were also investigated with the calculation of the PSD for every 20 s and 1 min. Figure 3.2.4 is the PSD compared to the first segment A1 (1 min calculation) and Figure 3.2.5 is the PSD compared to the first segment D1 (20 s calculation) for three subjects. Figure 3.2.6 is the comparison result between two signals. The variation of PSD with 1 min as the calculated duration didn’t show obvious difference under LFN and PN exposure for each subject. There were different amplitudes, but the changed trends were similar. The result of θ band for P2 got a high statistical significant correlation, which might be due to his almost equal annoyance evaluation to LFN and PN. Although the main result was similar as the previous result, more variation details were found with 20 s as the calculated duration. The PSD of θ band before D4 showed obvious differences among three subjects, and the amplitude had a positive correlation with the annoyance value result. When comparing the results of LFN and PN, the PSD over time under PN exposure was similar for all three subjects, and the obvious PSD changes under LFN exposure was found in the first half of θ band. And the changing trends for P1, P2 were similar at the beginning and in the opposite for P3, but in the latter part the variation of the three subjects showed no distinct difference.

The average RPSD results and variation of PSD over time in the Temporal Lobe indicated that there were different brain reactions to two different noises with the same level for each subject, but which EEG bands had the obvious difference was individual. The power changing of α and β band showed a negative relation trend with the evaluated annoyance value. The average RPSD of θ band and especially the power variation in the first 1 min got a positive relationship with the evaluated annoyance value. These findings were agreed with some conclusions from other studies that β band especially over temporal area was implicated in emotional phenomena, and more β activity was presented during positive than during negative emotional tasks (Ray and Cole, 1985), and the increased θ band might accompany both cognitive and emotional activation (Stenberg, 1992).

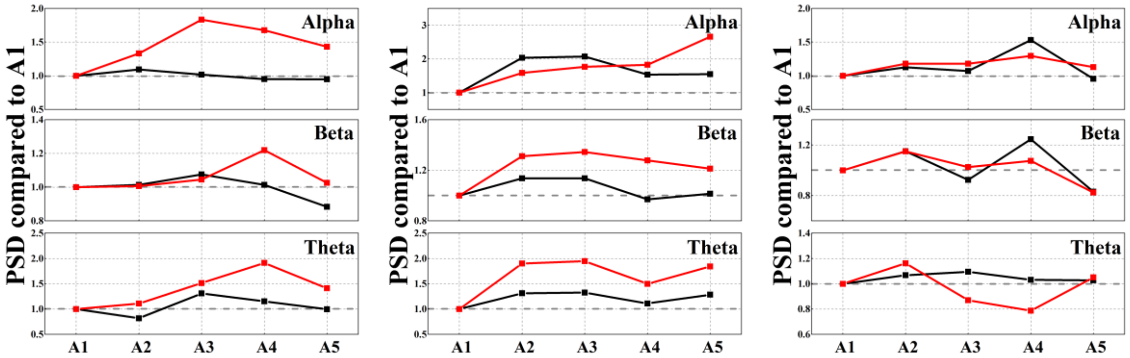


Figure 3.2.4 The PSD of EEG bands compared to A1 (the first 1 min EEG data) for three subjects (P1- left, P2- middle, P3- right)

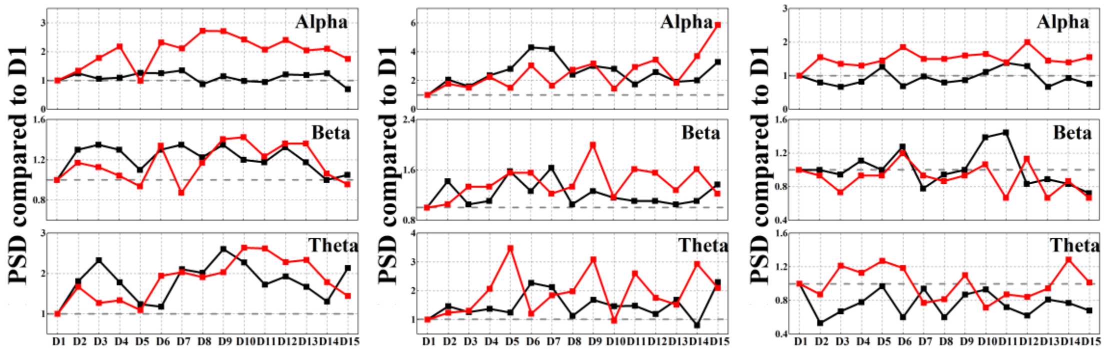


Figure 3.2.5 The PSD of EEG bands compared to D1 (the first 20 s EEG data) for three subjects (P1- left, P2- middle, P3- right)

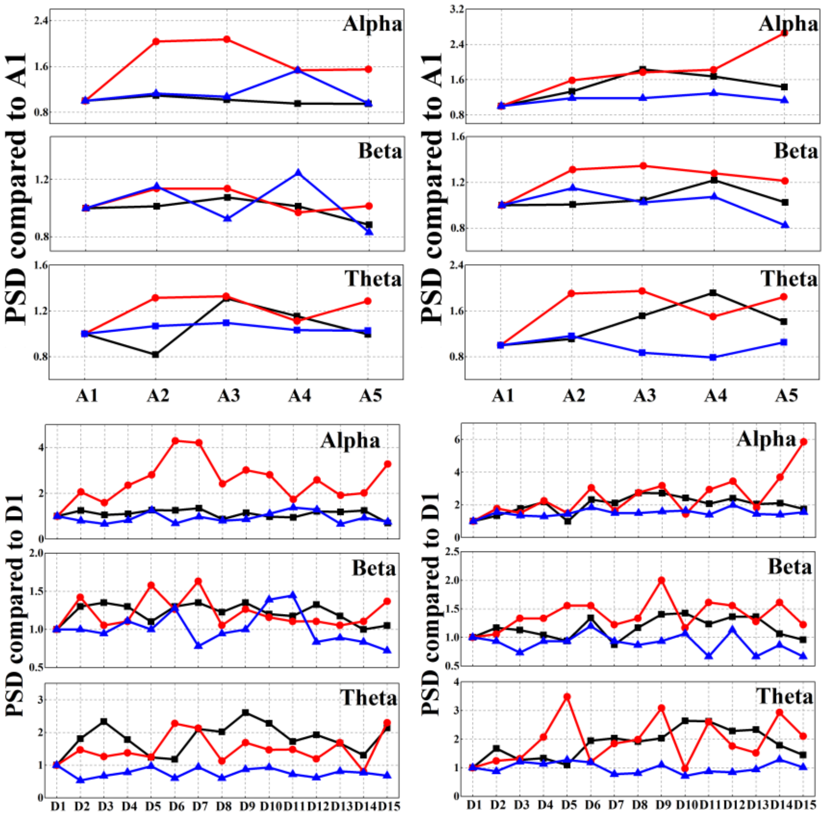


Figure 3.2.6 The PSD of Alpha, Beta and Theta bands compared to A1 (the first 1min EEG data) and D1 (the first 20s EEG data) for LFN (L) and PN (R)

3.3 The brain observation of LFN combined with different bandwidths PN

The listening test in section 3.1, which proved the feasibility of the indirect method to reduce the annoyance caused by LFN, was made in China. The living environment and culture were different between Chinese and German, so it was possible that their perceptions and reactions on LFN were different and the effect of the indirect method could also be different for them. Therefore, it was necessary to repeat the similar test with German subjects to find out whether using additional components with original LFN could also reduce their annoyance. In addition, brain reactions to LFN and LFN combined with extra components were observed. In general, the purposes of this listening test and EEG measurement were to investigate the feasibility of the indirect method for German subjects and to find out the brain variations caused by this sound adjustment method.

3.3.1 Subjects and questionnaire investigation

There were twelve German students from the University of Wuppertal as the subjects in the test. They answered the HP, GNS and GHQ questionnaires before the EEG measurement.

3.3.2 Experimental signals and EEG arrangement

Two same LFN signals used in the experiment 3.1 were selected for this test, which were LFN1 and LFN4. The level of the LFN was also set at 45 dBA, and the additional components were bandwidths PN in 20 dB. Table 3.3.1 is the detail of the 10 stimuli in this test. S1 to S5 were LFN1 combined with PN and belonged to one group (Signal-Group1), and S6 to S5 which were LFN4 combined with PN belonged to the other signal group (Signal-Group2).

The Emotiv EEG neuroheadset was used for the EEG measurement. Firstly, subjects sat in the chair with their eyes closed and just listened to the signals with the sequence of S1 to S10, while their EEG was recorded at the same time. The duration of each signal was 2 min with 1 min pause in silence between two signals. After that they joined a subjective evaluation listening test to assess the annoyance level in a five level scale (1 - lowest and 5 - the highest annoying level). The sequence of playback was the same as in the EEG recording stage, but the duration of the signals in the listening test was 5 s with 3 s pause, which was the same arrangement as in the experiment 3.1. All the signals were played twice.

Table 3.3.1 The information of the signals in experiment 3.3.

Signal-Group1	Original LFN	added pink noise	**Signal-Group2**	Original LFN	added pink noise
S1	LFN1		**S6**	LFN4	
S2	LFN1	200 Hz - 400 Hz	**S7**	LFN4	160 Hz - 630 Hz
S3	LFN1	200 Hz - 4K Hz	**S8**	LFN4	160 Hz - 2500 Hz
S4	LFN1	500 Hz - 1K Hz	**S9**	LFN4	400 Hz - 1600 Hz
S5	LFN1	2K Hz - 4K Hz	**S10**	LFN4	2K Hz - 4K Hz

3.3.3 Data analysis

The repeat reliability obtained from the subjective evaluation listening test was used as the rule to select the valid data. The EEG device - Emotiv EEG neuroheadset was more suitable for the human-computer interaction field, and it had a limitation that the impedance of electrode was sometimes too high. The artifacts rejection was processed with EEGLAB, and then PSD was calculated with the clean EEG data. Considering the reliability result and EEG result only the data of seven subjects were used in the next analysis progressing. Table 3.3.2 is the questionnaire results of these seven subjects.

Table 3.3.2 The information of subjects and summarized questionnaire results (classification rules are Table 2.2.1; in GNS questionnaire: A-leisure, B-work, C-habitation, D-communication and E-sleep).

Subjects	Age	Gender	HP	GHQ	GNS						GNS groups
					Sum	A	B	C	D	E	
P1	31	M	G2	G2	54	11	14	11	6	10	G2
P2	26	M	G1	G2	34	2	7	8	6	11	G3
P3	22	M	G2	G2	56	11	7	13	5	19	G2
P4	24	M	G2	G2	58	13	13	11	12	7	G2
P5	20	W	G2	G2	47	10	4	11	11	8	G2
P6	30	W	G1	G1	49	7	14	12	7	8	G2
P7	24	M	G2	G2	67	11	17	10	12	15	G2

Figure 3.3.1 shows the SAV results for all 7 subjects and the average SAV for two signal groups. The abbreviated form of the subjective annoyance value (SAV) was the same as used in experiment 3.1, but the range of SAV in this experiment was from 1 to 5. Although the amount of subjects was small, some trends could still be found. For example, P2 had low GNS and his SAV for all signals was obviously lower than the others. The average SAV of LFN1 combined with PN in 500 - 1K Hz was found lower than the SAV of LFN1, and the SAV of LFN4 combined with 200 - 400 Hz was lower than that of LFN4.

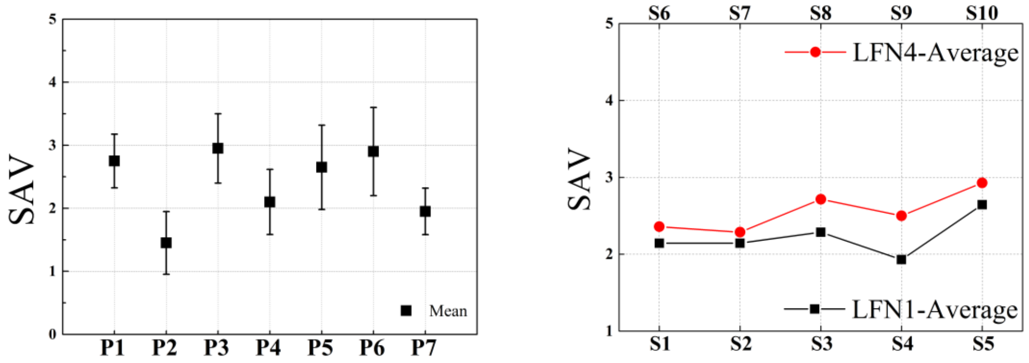


Figure 3.3.1 The SAV (range from 1 to 5) results for 7 subjects (mean value and SD) and the average SAV (range from 1 to 5) for two signal groups

Figure 3.3.2 depicts the SAV results for gender, HP, GNS and GHQ groups. Comparing between different groups, it was found that the SAV of GNS-G2 was all higher than that of GNS-G3, and the female subjects got higher SAV than the male subjects for all signals. The SAV of GHQ-G1 was higher than GHQ-G2 in Signal-Group1 but not for all the values of

Signal-Group2. The results for HP groups were just opposite that the SAV for HP-G2 was higher than HP-G1 in Signal-Group2, but not for all signals in Signal-Group1. The analyzing result of the subject groups which had lower SAV of LFN combined with PN than the SAV of original LFN indicated that the annoyance reducing effect using the indirect method got better results or was more suitable for HP-G1, GHQ-G1 and female subjects. Because the experimental environment and representing device was not the same as in the experiment 3.1, it could not directly be compared to the effect of the indirect method between Chinese and German subjects. But the decreased SAV results of adding bandwidths PN with LFN confirmed the feasibility of the indirect method for German subjects.

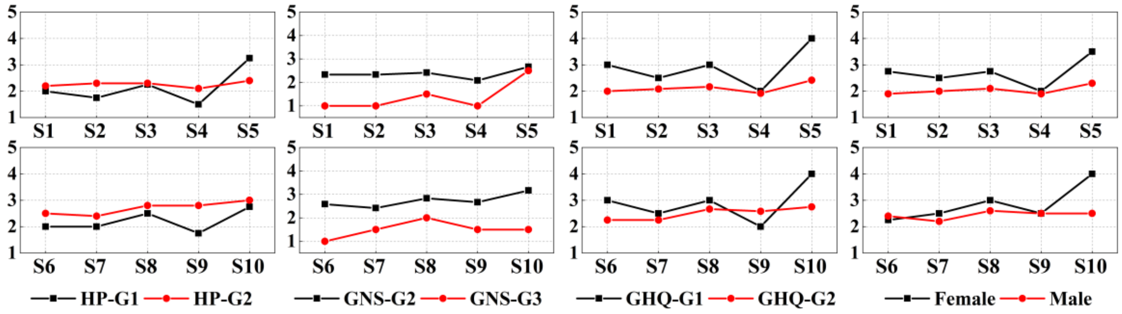


Figure 3.3.2 The comparison of SAV between HP, GNS, GHQ groups and genders

(X axis - two signal groups; Y axis - SAV (range from 1 to 5))

Due to the same reason mentioned in experiment 3.2, the relative PSD (RPSD) was used to compare between signals and to calculate the correlation with SAV. There were two LFN signals in the test, so the RPSD were calculated based on different LFN signals, which meant that the reference value in the RPSD calculation for Signal-Group1 was the PSD of LFN1 (S1) and for Signal-Group2 was the PSD of LFN4 (S6). Figure 3.3.3 shows the RPSD of θ, α and β band for each subject. And Figure 3.3.4 represents the RPSD result of each signal. The results briefly indicated that adding different bandwidths PN with LFN could cause obvious different brain reactions, which was supposed to be the explanation of the different annoyance results assessed by the subjects. And the analysis of the relation between SAV and the brain reaction, which was represented by the PSD of different EEG bands, was made with more data processing and statistical methods in the following.

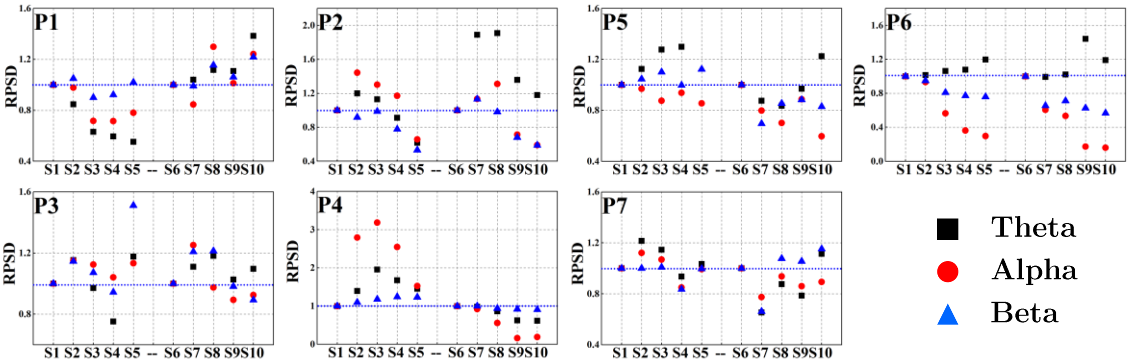


Figure 3.3.3 The RPSD of Theta, Alpha and Beta bands for each subject

(X axis - 10 test signals; Y axis - RPSD value)

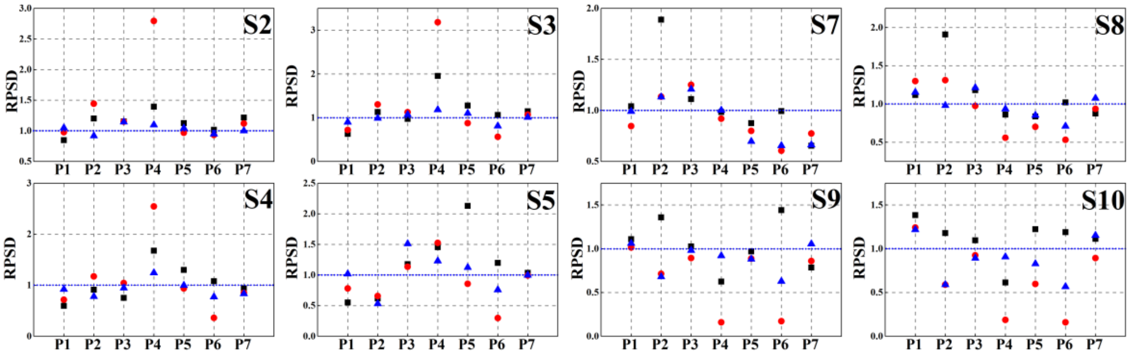


Figure 3.3.4 The RPSD results for S2-S5 and S7-S10

(legends are the same in Figure 3.3.3)(X axis - 7 subjects; Y axis - RPSD value)

The average RPSD of two signal groups for different questionnaire groups are summarized as in Figure 3.3.5. The RPSD of α and β bands varied similar for two HP groups, only that for HP-G1 was higher than the value for HP-G2. The variation of θ band for Signal-Group2 between two HP groups was almost in the opposite. Similar relation results were also obtained for GHQ groups and for different gender. The difference between GNS groups was found at β band in both signal groups and θ band for Signal-Group2.

Then the differences between groups were checked with AVOVA in SPSS, and the significant results were marked with color blue (Table 3.3.3). The significant results of HP groups were found at α and β band for both signal groups but the obvious difference at θ band was only found for Signal-Group2. Similarly, for GNS groups the significant results for two signal groups were not consistent; for Signal-Group1 the significant difference was only found at β band, and for Singal-Group2 the differences were found for θ and α band. The results of GHQ and gender were similar, significant results were found at α and β band for both signal groups. Particularly, the RPSD of β2 were different in most situations.

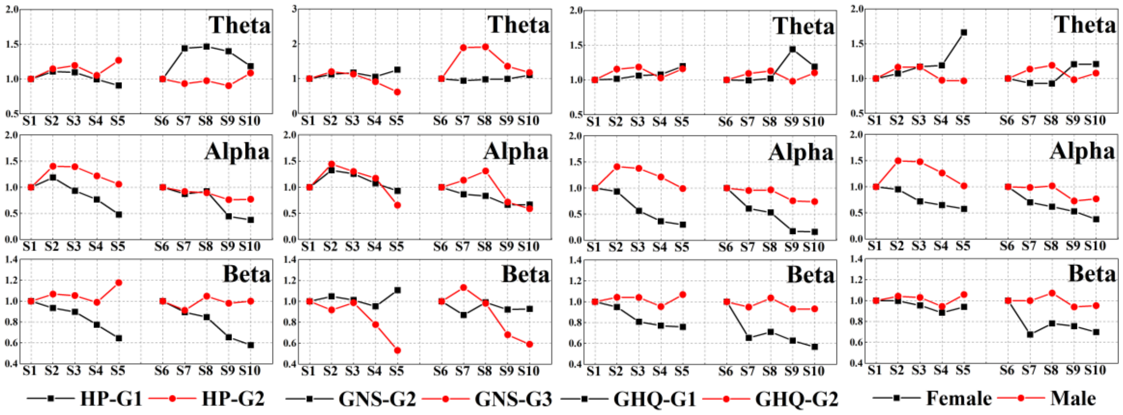


Figure 3.3.5 The comparison of RPSD between HP, GNS, GHQ groups and genders

(X axis - 10 test signals; Y axis - RPSD value)

Table 3.3.3 The ANOVA results of RPSD for HP, GNS, GHQ groups and genders (*p* value).

S1-S5	HP	GNS	GHQ	genders	S6-S10	HP	GNS	GHQ	genders
θ	.107	.213	.511	.224	θ	**.010**	**.039**	.473	.777
θ1	.368	.578	.633	.185	θ1	**.020**	.065	.844	.602
θ2	.157	.051	.379	.133	θ2	**.019**	**.041**	.618	.507
α	**.047**	.990	**.010**	**.008**	α	.316	.358	**.047**	.069
α1	.068	.852	**.016**	.068	α1	.929	.112	**.025**	**.048**
α2	**.036**	.828	**.005**	**.003**	α2	.212	.698	.052	.072
β	**.020**	.082	**.015**	.074	β	**.044**	.555	**.011**	**.010**
β1	.082	.187	.113	.170	β1	.076	.949	**.010**	**.013**
β2	**.007**	**.034**	**.006**	**.018**	β2	**.049**	.563	**.014**	**.010**
β3	**.021**	**.016**	.479	**.009**	β3	.053	.353	**.011**	**.005**

The correlation relations between the average SAV of all subjects and the average RPSD for each position and the overall average result were calculated and summarized in Table 3.3.4. Figure 3.3.6 is the used EEG electrode positions. The positive correlations were marked in red and the negative correlations in blue. The positive relation between SAV and RPSD of θ, θ1 and θ2 band at the temporal area was agreed with the result obtained from experiment 3.2. And the negative relation results between RPSD of α bands and SAV which were found in almost the whole scalp was consistent with the result of Saito (Saito, 1988) - that changes in brain waves depended on the subjects' psychological response, whether they regarded a sound as unpleasant, and the α wave decreased when a subject indicated discomfort. The relation between RPSD of β band and SAV was negative at the temporal area which was the same result as before, and the negative correlation was also found at the frontal area.

Table 3.3.4 Correlation results between the average SAV of seven subjects for all signals and the average RPSD of EEG bands at different electrode positions (* $p<0.05$, ** $p<0.01$).

	θ	θ1	θ2	α	α1	α2	β	β1	β2	β3
AF3	.167	.138	.272	**-.633***	-.517	**-.670***	.162	-.163	0.000	.107
AF4	-.199	-.120	.009	**-.816****	**-.755***	**-.835****	-.180	-.131	-.264	-.144
F3	.238	.531	.452	**-.670***	-.394	**-.676***	.193	.278	-.164	.522
F4	-.144	.095	-.153	**-.755***	**-.737***	**-.792****	-.537	-.340	**-.632***	**-.681***
F7	.284	.253	.242	-.407	-.028	-.383	-.364	-.193	-.383	-.272
F8	.383	.526	.368	**-.835****	**-.827****	**-.802****	-.278	-.068	-.572	-.307
FC5	.525	.602	.382	**-.633***	-.196	-.494	.009	-.003	.095	-.052
FC6	.421	.333	**.719***	**-.823****	**-.788****	**-.823****	-.297	.043	-.223	.241
O1	-.083	-.198	-.113	**-.725***	**-.810****	**-.737***	-.468	-.352	-.450	-.535
O2	-.012	.469	.239	-.558	**-.767****	-.382	-.225	-.449	.034	.166
T3	**.693***	**.868****	**.633***	-.500	-.236	-.554	.303	.117	.374	.387
T4	.358	.541	.480	**-.749***	**-.778****	**-.651***	-.129	-.160	-.110	.368
T5	.611	**.672***	.584	-.604	-.286	**-.651***	.352	.331	**-.694***	.548
T6	-.405	-.138	-.391	**-.688***	**-.829****	-.498	**-.645***	**-.672***	-.420	-.154
All	.320	.552	.365	**-.798****	**-.737***	**-.645***	-.339	-.404	-.272	-.012

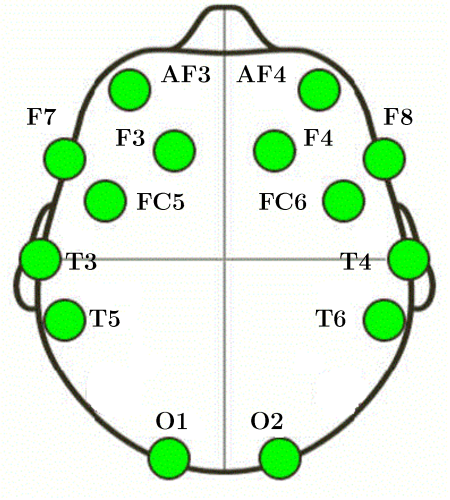


Figure 3.3.6 The used EEG electrode positions in experiment 3.3

Some conclusions were obtained from the above results. Firstly, the SAV results from the listening test confirmed that the indirect method could also reduce the annoyance caused by LFN for German subjects. Personality traits showed some certain influence on the SAV results, for example, one subject with lower GNS assessed all the signals less annoying than the others, subjects with relative poor mental performance got a little bit higher SAV result and the SAV of the female subjects was higher in average than that of the male subjects. And the annoyance reducing effect was found more suitable for subjects belonging to HP-G1, GHQ-G1 and for female subjects. Then the EEG results indicated that the exposure to LFN combined with different bandwidths PN could cause different brain reactions, and there were similar RPSD variation trends for α and β band between questionnaire groups. The significant ANOVA results for GHQ groups and gender were consistent, but for HP and GNS groups they were not the same for two signal groups. After that the correlation calculation was made between RPSD and SAV, and the results showed that annoyance changings caused by LFN combined with PNs had a negative relationship with RPSD of θ band at the temporal area and a positive correlation result with RPSD of α band at the whole scalp. It was also in a negative relation with RPSD of β band at frontal and temporal areas. These findings indicated that when subjects were under the exposure to bandwidths PN combined with original LFN, their cerebral cortex which had the function related with auditory and emotions showed corresponding power changes. The brain variation was supposed having a function to the annoyance changings in the subjective evaluation test, and the correlation results proved this hypothesis. In this processing, the personality traits such as the GNS, mental situation or gender showed different certain effects.

3.4 Different brain reactions between normal subjects and LFN sufferers

The results of experiment 3.1, 3.2 and 3.3 showed that the indirect method had a positive effect to help normal subjects with high or normal GNS to reduce the annoyance caused by LFN, and their brain reaction to different LFN situations could be observed well with EEG. Since one of the aims of the whole thesis was to investigate the different perceptions and reactions on LFN between LFN sufferers and the reference subjects, in this section the similar indirect method listening test and EEG measurement were made with these two types of subjects to find out whether there were significant different objective and subjective results between them. In addition, relative hearing threshold test and low frequency sensitivity test were also made to observe fundamental aspects whether there were obvious different hearing abilities or low frequency sensitivities between them. The questionnaires appeared in the other experiments and some new ones were used, and the annoyance assessments and brain reactions between different classified questionnaire groups were also compared.

3.4.1 Subjects

Fourteen subjects joined the test. Eleven students (8 males and 3 females) from the University of Wuppertal were chosen as the reference group. The generalization from experiences made, indicated that for the reference group subjects didn't claim to be suffering from LFN, the general results would not change with an increase of the number of test subjects (Poulsen, 2003). A small group of people who reported suffering from LFN in their home was named 'LFN sufferer group', which consisted of 3 female subjects. The basic information of all subjects is in Table 3.4.1.

Table 3.4.1 The basic information of all subjects in experiment 3.4.

Group	**Subject**	**Gender**	**Age**	**National**
Reference group	P1	F	31	Chinese
	P2	M	30	German
	P3	M	26	Chinese
	P4	F	33	Turkey
	P5	M	31	German
	P6	M	20	German
	P7	M	29	German
	P8	F	27	Chinese
	P9	M	27	Spanish
	P10	M	32	Chinese
	P11	M	28	Chinese
LFN sufferers	S1	F	47	German
	S2	F	65	German
	S3	F	49	German

3.4.2 Experiment material and procedure

First of all, the subjects joined a relative hearing threshold test, and then followed with two subjective evaluation listening tests, which were the low frequency sensitivity test and the indirect method test. After that they answered several questionnaires, which were the Edinburgh inventory, GHQ, GNS, LFNS, PANAS and PSS. In the meantime, the EEG device was prepared so at the EEG measurement stage brain reactions to different noise exposures obtained from the two listening tests were recorded. At the end there was another short listening test to obtain the subjective annoying value (SAV) results of the same signals that appeared in the EEG measurement for each subject. The Figure 3.4.1 illustrates the procedure of the whole experiment.

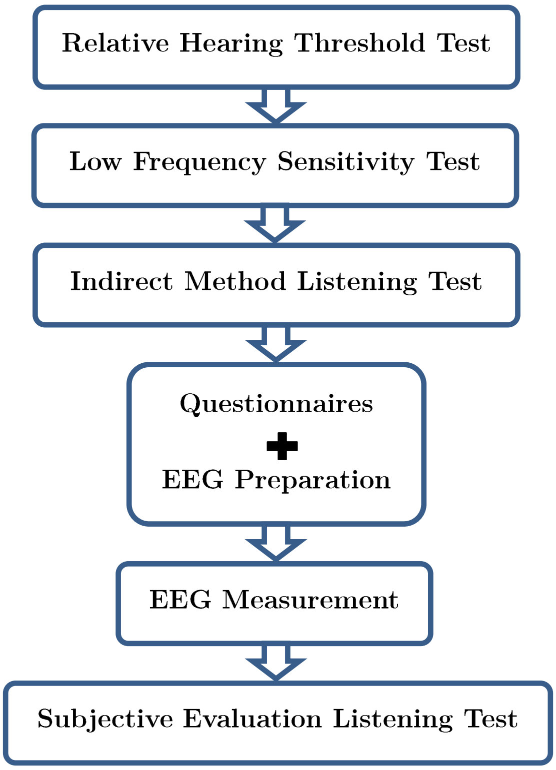


Figure 3.4.1 The procedure of experiment 3.4

- **Relative hearing threshold test**

There are two methods that can be used to measure the absolute hearing threshold (Gelfand, 2009). Minimal Audible Field (MAF) involves the subject sitting in a sound field and stimuli are presented via a loudspeaker. The sound level is then measured at the position of the subject's head with the subject not in the field. The other method, Minimal Audible Pressure (MAP) involves presenting stimuli via headphones and measuring sound pressure in the subject's ear canal with a very small probe microphone. These two different methods produce different thresholds, and considering all the used auditory stimuli presented via loudspeakers, MAF was selected here. The reason why it was called relative hearing threshold test was that it did not measure the individual absolute hearing threshold according to the standard for each subject, but rather to check whether the subjects could hear different SPLs higher than the average hearing threshold values. And the purpose was to measure whether the involved subjects had relative normal hearing ability for the following LFN related listening test.

To meet the environmental demands according to the standard ISO 8253-2 (ISO, 2009) and reduce the error caused by different heights of the subjects, the SPLs in a distance of 15 cm to the right and left, 15 cm above and below of the reference point were measured for all the test frequencies, and the differences were found within ±2 dB from the level in the reference point.

The reference point was the approximate middle of two ears when the subjects sat in the chair for the whole experiment. Also the SPLs on the axis from the loudspeaker through the reference point at positions of 10 cm in front and behind the reference point were also within ± 1 dB. The measurement results met the criterion.

The chosen SPLs of the test signals were 10 dB (10 HL), 15 dB (15 HL) and 20 dB (20 HL) higher than the average absolute hearing threshold. There were also silence signals among the PTs in case the subjects gave false answers. The subjects were asked to only push a button when they heard a PT after the tip sound (440Hz), and at the same time a signal was sent to the computer to note the results. Figure 3.4.2 depicts the structure of each test signal, and Table 3.4.2 depicts the arrangement of the signals. The playback sequence was 15 HL, 10 HL, 15 HL and 20 HL. The correctness of the identification for silence signals and the amount of the same choices for twice 15 HL trials were used as the reliability.

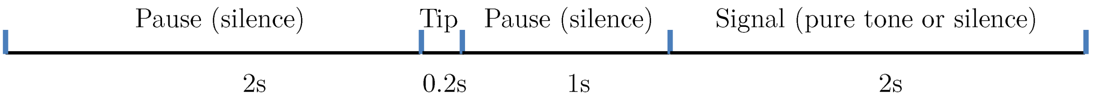


Figure 3.4.2 The structure of the signal in the relative hearing threshold test

Table 3.4.2 The arrangement of the test signals in the relative hearing threshold test.

Signal sequence	The frequency of the test signals (Hz)		
	10 HL	**15 HL**	**20 HL**
1	1000	100	200
2	40	2000	160
3	63	31.5	1000
4	16000	160	8000
5	250	63	**Silence**
6	**Silence**	80	100
7	100	**Silence**	4000
8	31.5	1000	2000
9	8000	200	63
10	**Silence**	**Silence**	50
11	125	50	250
12	200	500	**Silence**
13	160	250	125
14	50	8000	500
15	80	16000	80
16		125	16000

- **Low frequency sensitivity test**

The low frequency sensitivity listening test was designed based on the standard DIN 45680, because the great majority of LFN problems from industrial sources were tonal, and for tonal frequencies the allowable noise limit was less than for non-tonal noises. It was presumed that LFN with tonal character could cause external annoyance, and people might have different sensitivities in the low frequency range. The original LFN in the test was Brown noise through a low pass filter with the cut-off frequency as 100 Hz and order at 5 with SPL at 40 dBA. The other signals were LFN combined with PT at 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, 80 Hz and 100 Hz. The SPLs of the PTs were not the same. The rule was followed by the DIN 45680 that the SPL of the particular frequency was only 5 dB higher than the two neighboring 1/3 Oct bands.

The Pair-wise comparison method was used as the evaluation method. This method has been widely used in the research of acoustic quality, which requires subjects to compare the degree of annoyance between two noise samples those are represented in pairs. The comparative process in pair-wise comparison is simpler than the rank method, and it is easier for the subjects to make a decision about which sample is more annoying than the other one. Table 3.4.3 is the signal arrangement for the test. Subjects evaluated which signal in one pair was more annoying with the same button used for the relative hearing threshold test. One press was for the first signal and twice was for the second signal. Then they needed to evaluate loudness in the same way. Figure 3.4.3 shows the structure of one pair signals. The same pair of signals with opposite sequences was designed to get the individual reliability.

Table 3.4.3 The sequence of the signals in the low frequency sensitivity test.

sequence number	**Signal 1**	**Signal 2**	**sequence number**	**Signal 1**	**Signal 2**
1	LFN+80Hz	LFN+50Hz	16	LFN+63Hz	LFN
2	LFN	LFN+40Hz	17	LFN+50Hz	LFN+100Hz
3	LFN+40Hz	LFN+100Hz	18	LFN+63Hz	LFN+80Hz
4	LFN	LFN+63Hz	19	LFN+80Hz	LFN+63Hz
5	LFN	LFN+80Hz	20	LFN+80Hz	LFN+100Hz
6	LFN+100Hz	LFN+50Hz	21	LFN+40Hz	LFN+80Hz
7	LFN+80Hz	LFN+40Hz	22	LFN+80Hz	LFN
8	LFN+50Hz	LFN	23	LFN+63Hz	LFN+100Hz
9	LFN+100Hz	LFN+63Hz	24	LFN+40Hz	LFN
10	LFN	LFN+50Hz	25	LFN	LFN+100Hz
11	LFN+50Hz	LFN+80Hz	26	LFN+63Hz	LFN+40Hz
12	LFN+50Hz	LFN+63Hz	27	LFN+100Hz	LFN+80Hz
13	LFN+100Hz	LFN	28	LFN+50Hz	LFN+40Hz
14	LFN+100Hz	LFN+40Hz	29	LFN+63Hz	LFN+50Hz
15	LFN+40Hz	LFN+50Hz	30	LFN+40Hz	LFN+63Hz

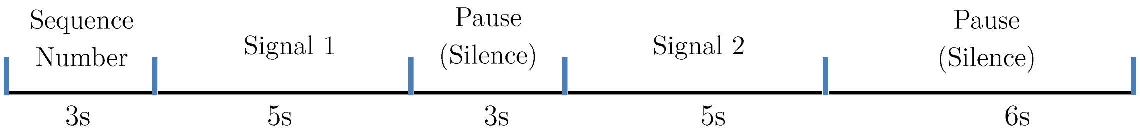


Figure 3.4.3 The structure of one pair signals in the low frequency sensitivity test

- **Indirect method listening test**

The feasibility of the indirect method was proven in experiment 3.1 and 3.3. The purpose of the repeating test was to find out whether it had a particular effect for LFN sufferers and to check the difference between subjects with new added personality traits. The signals in this test were the same LFN used in the last listening test and LFN combined with PN in different bandwidth ranges, which were 250-500 Hz, 500-1K Hz, 1K-4K Hz and 4K-8K Hz. The SPL of the PN was 20 dB, which according to the primary test was at a suitable level (He et al., 2014). The evaluation method was different from the earlier tests, which was the Pair-wise comparison method, and the same evaluation rule as in the low frequency sensitivity test was used to assess the annoyance and loudness. Table 3.4.4 is the signal arrangement.

Table 3.4.4 The arrangement of the signals in the indirect method test.

sequence number	**Signal 1**	**Signal 2**	**sequence number**	**Signal 1**	**Signal 2**
1	LFN	LFN+4K-8KHz	11	LFN+500-1KHz	LFN+250-500Hz
2	LFN+4K-8KHz	LFN	12	LFN	LFN+500-1KHz
3	LFN+250-500Hz	LFN+4K-8KHz	13	LFN+250-500Hz	LFN+500-1KHz
4	LFN+500-1KHz	LFN+1K-4KHz	14	LFN+4K-8KHz	LFN+500-1KHz
5	LFN+250-500Hz	LFN	15	LFN	LFN+1K-4KHz
6	LFN+1K-4KHz	LFN	16	LFN+4K-8KHz	LFN+250-500Hz
7	LFN+250-500Hz	LFN+1K-4KHz	17	LFN+500-1KHz	LFN+4K-8KHz
8	LFN+1K-4KHz	LFN+250-500Hz	18	LFN+4K-8KHz	LFN+1K-4KHz
9	LFN+1K-4KHz	LFN+500-1KHz	19	LFN	LFN+250-500Hz
10	LFN+1K-4KHz	LFN+4K-8KHz	20	LFN+500-1KHz	LFN

In general, there were additional components combined with the same original LFN in both subjective evaluation listening tests, but the added component was supposed to increase the subjective annoyance in one test and might decrease the negative effect caused by LFN in the other one. Therefore, the combination of the highest annoyance value in the low frequency sensitivity test and the one of the lowest annoyance value in the indirect method were obtained for each subject, and these two signals were used as the auditory signals in the following EEG test.

▪ EEG recording

The used EEG device was Neuron-Spectrum-5, and the electrode positions are the positions colored in yellow in the Figure 3.4.4. EOG at the both external canthus was also recorded to monitor the eye movement and help identify the artifacts in the analysis stage. Two of the auditory signals used in the EEG measurement stage (LFN+PT, LFN+PN) were individual for subjects, which depended on their two listening tests results as mentioned above. But the LFN and PN (40 dBA) were the same for all subjects. Figure 3.4.5 is the signal arrangement of the EEG measurement. The duration of each signal stage was 2 minutes, for the pause it was 1 minute. During the EEG measurement the subjects were asked to sit comfortably in the chair, close their eyes, try to keep still, and just listen to the noise without any other demands.

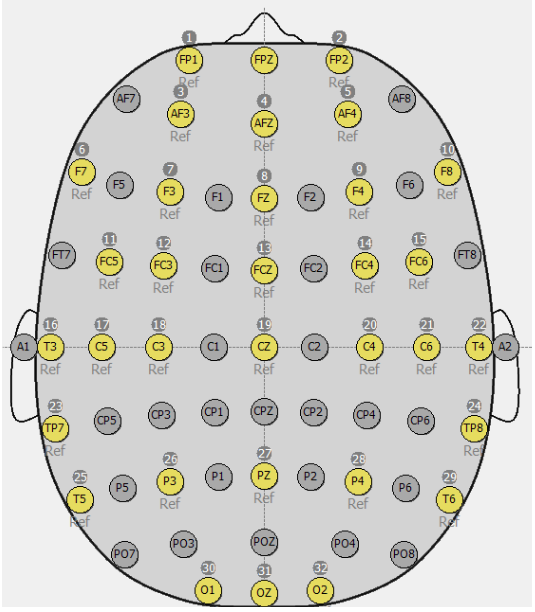


Figure 3.4.4 The chosen electrode positions in the EEG experiment

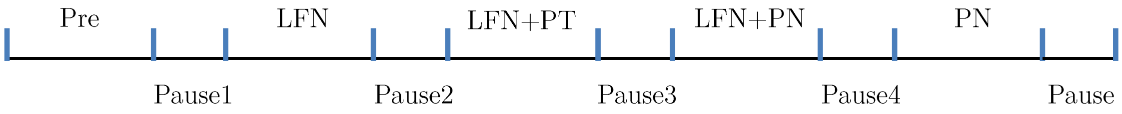


Figure 3.4.5 The structure of the signals in the EEG measurement stage

▪ Final subjective listening test

At the end there was a short listening test with the same noise signals used in the EEG measurement for each subject. They needed to evaluate the annoyance and loudness level for each signal again. The magnitude estimation method with 11 levels evaluation criterion was used in this part, with level 1 for the lowest annoyance or loudness, and level 11 for the highest. Because the subjects were already familiar with the signals, it would be relatively easy for them to give their assessments and the result was presumed reliable. The duration of each noise sample was 5 s, with an interval of 3 s. All four signals were repeated three times in a random order. Then the average SAV and loudness of three times were calculated as the final results for the further analysis.

3.4.3 Data analysis

3.4.3.1 The results of questionnaires

The classification and detailed results of all questionnaires were collected as in Table 3.4.5 and Table 3.4.6. The classification rules were as described in Chapter 2. There were certain subjects classified into different groups, which enabled a comparison of their differences with statistical methods. The LFN sufferers were found obviously very sensitive to LFN, but only one was found very sensitive to general noise. Three LFN sufferers all had high GHQ scores and two of them got higher PSS score, which indicated that they had poor mental performance and also were under high stress. They all complained the very strong negative influence of LFN on their normal life, and especially when sleeping.

Table 3.4.5 The classification of used questionnaires (classification rules are Table 2.1.1).

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	S1	S2	S3
GNS	**G1**	G2	G2	G2	G2	G2	G2	G2	G2	G2	**G1**	**G1**	G2	G2
LFNS	**G1**	G2	G2	**G1**	G2	G2	G2	G2	G2	G2	**G1**	**G1**	**G1**	**G1**
GHQ	**G1**	G2	G2	G2	G2	G2	G2	**G1**	G2	G2	**G1**	**G1**	**G1**	**G1**
PANAS	**G1**	G2	G2	**G1**	G2	G2	G2	G2	G2	G2	**G1**	G2	**G1**	**G1**
PSS	**G1**	**G1**	G2	**G1**	G2	G2	G2	G2	G2	G2	G2	G2	**G1**	**G1**

Table 3.4.6 The detailed results of used questionnaires (the details of the sub-scales of GNS and GHQ questionnaire are in Table 3.4.7 and 3.4.8).

	GNS						**LFNS**		**GHQ**					**PANAS**		**PSS**
	Sum	A	B	C	D	E	LFNS-1	LFNS-2	Sum	F	G	H	I	PA	NA	
P1	71	16	12	15	12	16	17	4	43	10	9	15	9	18	23	33
P2	59	11	12	10	14	12	11	2	18	6	4	5	3	40	20	28
P3	52	9	13	13	8	9	11	3	7	3	0	4	0	39	10	18
P4	59	13	14	10	8	14	17	4	23	6	7	9	1	28	25	31
P5	41	10	11	11	8	1	13	3	9	1	4	4	0	40	19	19
P6	51	10	14	11	10	6	7	2	17	4	2	10	1	33	17	20
P7	68	15	16	17	9	11	12	3	11	2	2	7	0	36	15	21
P8	56	9	10	11	8	18	11	2	24	7	6	9	2	31	14	22
P9	59	11	15	5	13	15	10	3	15	6	4	5	0	37	20	18
P10	53	13	10	13	10	7	10	2	23	6	9	7	1	35	17	21
P11	74	14	14	17	10	19	16	4	27	6	7	6	8	22	18	23
S1	91	18	18	17	19	19	17	5	60	10	20	19	11	39	12	20
S2	65	11	13	14	10	17	17	5	54	16	14	13	11	18	33	30
S3	69	16	14	14	14	11	17	4	57	11	12	20	14	23	16	38

Except PSS, the other questionnaires had more than one sub-scale, therefore, besides the classification depended on the overall result, the results for sub-scales should also be considered. The percentages of subjects who got higher sensitivity in the five sub-scales distinguish between reference and LFN sufferer groups, were summarized in Table 3.4.7. The amount of the LFN sufferer group was small, but they all had high sensitivity for the noise from their habitation. On the other side, 45% of the reference showed sensitivity at work and sleep aspects, and only 27% and 9% in other parts in their life. Similarly, the percentages of subjects who had higher scores in each sub-scale of GHQ were shown in Table 3.4.8. The reference group had relative high score in performance at social dysfunction (36%), and in the other three aspects the percentages were very low. All LFN sufferers got high scores for four sub-scales of the GHQ questionnaire.

Table 3.4.7 The percentage of high score (≥ 14) for the five noise types in GNS questionnaire.

	A - leisure	B - work	C - habitation	D - communication	E - sleep
Reference	27%	45%	27%	9%	45%
LFN Sufferers	67%	67%	100%	67%	67%

Table 3.4.8 The percentage of high score (≥ 8) for the four sub-scales in GHQ.

	F - Somatic symptoms	G - Anxiety and insomnia	H - Social dysfunction	I - Severe depression
Reference	9%	18%	36%	9%
LFN Sufferers	100%	100%	100%	100%

Then Non-Metric Multidimensional Scaling (NMDS) was calculated to observe the differences between the subjects and to check whether the classification of the groups was statistically reasonable. NMDS is used widely in psychology to explore and discover the defining characteristics of unknown social and psychological structures (Gyslain Giguère, 2006), and it reveals the structure of a data set by plotting points in one or two dimensions. Table 3.4.9 shows the Stress and RSQ results obtained from NMDS calculation in SPSS. Stress values were calculated based on Kruskal's stress formula 1, which consisted of the square root of the normalized squared discrepancies between interpoint distances in the NMDS plot and the smoothed distances predicted from the dissimilarities. Stress varied between 0 and 1, Kruskal & Wish proposed meanings using the following levels : Stress > 0.2: Poor; 0.10 ≤Stress≤ 0.20: Fair; 0.05 ≤Stress≤ 0.1: Good; 0.025 ≤Stress≤ 0.05: Excellent; 0.00: Perfect (Kruskal and Wish, 1978). RSQ values were the proportion of variance of the scaled data (disparities) in the partition (row, matrix, or entire data), which was accounted for by their corresponding distances. All the RSQ results were near to 1, only the Stress value of the GNS group was relatively high, but also in an acceptable range. Figure 3.4.6 is the model results of NMDS. The distance between subjects in the Dimension 1 or 2 represented their similarity of the personality trait, and the adjacent ones could be considered as one group. The circled subjects got similar questionnaire results, which was not only relevant to the summary score from each questionnaire but also considering scores of the sub-questions. For example, P6 got the lowest LFNS score and was far away from the others, and P5 had the lowest GNS and S1 had the highest score which were both shown in the GNS result. Therefore, the NMDS results indicated that the classifications of GNS, LFNS, GHQ and PANAS have statistical meanings.

Table 3.4.9 The Stress and RSQ values of the NMDS calculation.

	Stress	**RSQ**		**Stress**	**RSQ**
NS	0.10789	0.94248	**GHQ**	0.04712	0.99271
LFNS	0.01256	0.99952	**PANAS**	0.00624	0.99984

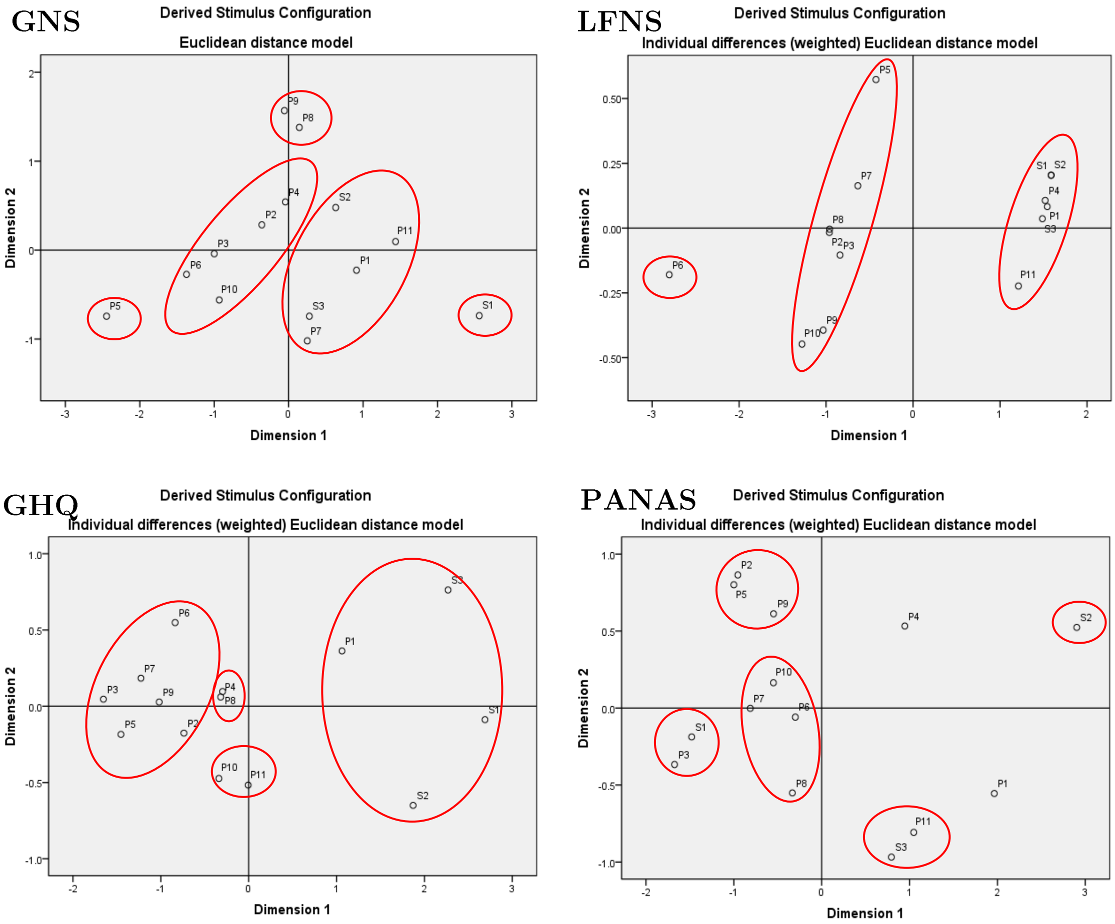


Figure 3.4.6 The NMDS results for different questionnaires

3.4.3.2 The results of the listening tests

- **The results of the relative hearing threshold test.**

The HL15 dB repetition rate and the accuracy of identifying the silence signals reflected the stability and repeat reliability for each subject, and the frequency deficiency showed the relative hearing ability in different frequency ranges (Table 3.4.10). All of the subjects met the requirement for the experiment for being able to hear the PTs with 20 dB higher than the average hearing threshold.

Table 3.4.10 The results of the relative hearing threshold test (* means that the subject could not hear the PT in 15 dB higher than the average hearing threshold).

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	S1	S2	S3
HL15 repeat (%)		75	94	94	88	100	94	88	94	94	88	63	94	94	100
Silence accuracy (%)		88	88	100	75	100	88	100	100	100	75	100	100	88	75
Frequency Deficiency (Hz) (HL 15)	31.5														
	40														
	50														
	63														
	80														
	100														
	125														
	160														
	200														
	250														
	500														
	1K													*	
	2K											*		*	*
	4K													*	*
	8K	*									*			*	
	16K	*		*		*							*	*	*

- **The results of the low frequency sensitivity test**

Table 3.4.11 summarizes the subjective annoyance and loudness results for the low frequency sensitivity test. The purpose of this test was to find out the most sensitive frequency lower than 100 Hz for each subject, so the collected result was each subject's calculation result. It showed that the evaluated annoyance of LFN combined with PT was higher than that of LFN, and the frequency was individual. The maximum subjective annoyance result for each subject was highlighted, and the corresponded combination was chosen to use in the EEG measurement stage for her/him. Noticeably, more than half of the subjects felt LFN combined with 40 Hz most annoying, and the loudest signal they evaluated was the LFN combined with 100 Hz. Less than half of them gave the same signal both the highest result for annoyance and loudness. The correlation result between annoyance and loudness (Table 3.4.12) showed that for most subjects there was no significant relationship between the annoyance and loudness evaluations for LFN combined with low frequency PT.

Table 3.4.11 The annoyance and loudness results of the low frequency sensitivity test (the marked result is each subject's highest annoyance or loudness value except the result of LFN).

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	S1	S2	S3
Annoyance	**LFN**	4	2	5	4	5	3	6	7	2	6	9	3	3	7
	+40Hz	**8**	5	**9**	5	6	**10**	**8**	**6**	6	3	**11**	**10**	7	**7**
	+50Hz	3	4	3	4	4	3	2	4	2	5	8	4	3	5
	+63Hz	2	3	3	**6**	4	5	4	3	4	4	8	7	5	5
	+80Hz	7	8	7	6	2	4	5	4	**9**	5	9	3	**8**	5
	+100Hz	6	**8**	3	5	**9**	5	5	6	7	**7**	10	3	4	1
Loudness	**LFN**	2	3	3	2	2	1	5	4	3	3	4	2	1	5
	+40Hz	7	8	7	7	5	7	6	8	5	5	9	**10**	6	6
	+50Hz	2	1	4	2	3	4	3	2	4	4	3	4	3	7
	+63Hz	3	3	1	2	3	2	3	2	3	2	**12**	7	7	2
	+80Hz	7	7	**8**	8	7	6	**7**	6	6	7	11	4	**7**	3
	+100Hz	**9**	**8**	7	**9**	**10**	**10**	6	**8**	**9**	**9**	10	3	6	**7**

Table 3.4.12 Correlation results between the evaluated annoyance and loudness of the low frequency sensitivity test for each subject.

	Correlation Coefficient	**Sig. (2-tailed)**		**Correlation Coefficient**	**Sig. (2-tailed)**
P1	.618	.191	P8	.561	.247
P2	.672	.144	P9	.809	.051
P3	.524	.286	P10	.377	.461
P4	.381	.456	P11	-.029	.956
P5	.235	.654	S1	**.893***	**.016**
P6	.618	.191	S2	**.836***	**.038**
P7	.582	.225	S3	-.25	.632

Then the average annoyance and loudness results of the reference group, LFN sufferers and different questionnaire groups were also calculated and summarized (Figure 3.4.7 and Figure 3.4.8). The obvious different relations for annoyance results were found for the value of LFN combined with 63 Hz, 80 Hz and 100 Hz between groups. For example, there was a significant negative relation between the reference group and LFN sufferers that the evaluated annoyance value was increased when the frequency of the added PT rose for the reference group, but the result for LFN sufferers was opposite. The difference between Chinese and German subjects (without LFN sufferers) was not obvious. The difference between other groups was only found for LFN combined with 100 Hz.

The difference of loudness results between groups was slight and the Paired T-test showed also no statistical significant result. These findings indicated that there were significant different annoyance perceptions and reactions on LFN combined with PT in low frequency ranges between LFN sufferers and the reference subjects. The other personality traits didn't show a strong influence on the result.

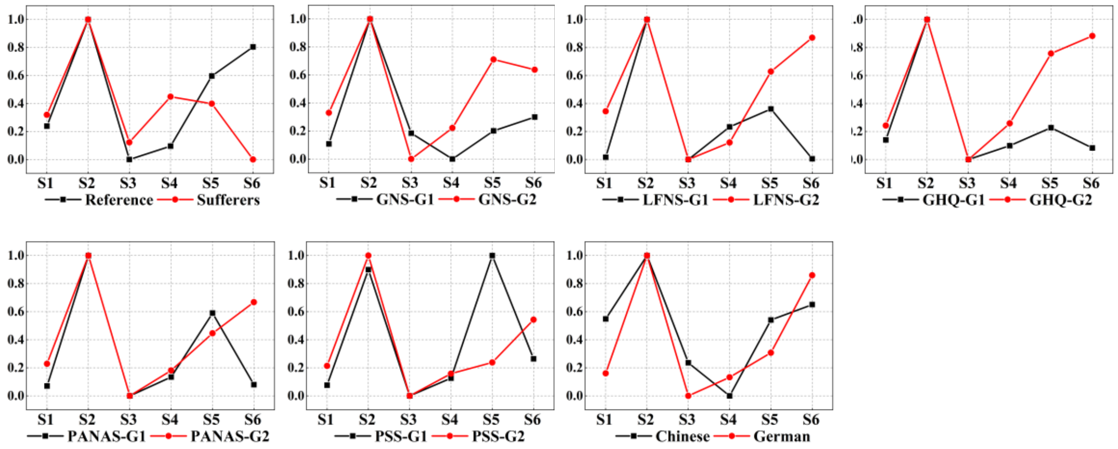


Figure 3.4.7 The comparison of the subjective annoyance results of the low frequency sensitivity test between subjects groups and between questionnaire groups

(X axis - test signals: S1 (LFN), S2 (LFN+40Hz), S3 (LFN+50Hz), S4 (LFN+64Hz), S5 (LFN+80Hz), S6 (LFN+100Hz); Y axis - SAV levels of the pair-wise comparison method)

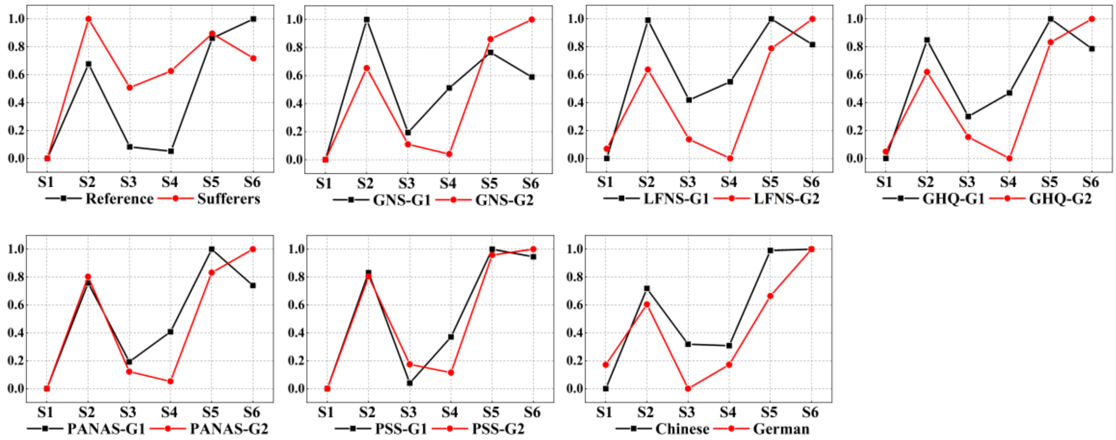


Figure 3.4.8 The comparison of the loudness results of the low frequency sensitivity test between subjects groups and between questionnaire groups

(X axis - the same signal arrangement as in Figure 3.4.7; Y axis - loudness level of the pair-wise comparison method)

- **The results of the indirect method test**

Similar calculation and analysis were made for the indirect method test. Table 3.4.13 resumes the annoyance and loudness result for each subject. Since the aim of the indirect method test was to find out the decreased effect on annoyance, the highlighted chosen results were the minimum annoyance value except the result of LFN. Although the annoyance of LFN combined with different PN was not always the minimum annoyance value for all subjects, for some subjects they still assessed LFN more annoying than LFN combined with PN in some pairs. Table 3.4.14 shows the correlation between annoyance and loudness.

Table 3.4.13 The annoyance and loudness results of the indirect method test (the marked result is each subject's lowest annoyance or loudness value except the result of LFN).

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	S1	S2	S3
SAV	LFN	1	1	1	1	1	2	5	0	5	2	2	2	5	3
	+250-500Hz	**3**	**1**	**3**	5	**2**	**2**	5	**3**	**2**	7	3	5	**2**	**3**
	+500-1KHz	5	6	6	7	3	3	4	5	4	**1**	6	**4**	3	3
	+1K-4KHz	6	8	5	4	6	7	**1**	6	5	6	7	5	5	4
	+4K-8KHz	5	4	5	**3**	8	6	5	6	4	4	**2**	4	5	7
Loudness	LFN	2	3	2	4	2	3	1	2	1	4	2	2	4	6
	+250-500Hz	4	4	**0**	**3**	3	**3**	**1**	3	**3**	5	**1**	5	5	4
	+500-1KHz	**2**	**3**	5	5	**2**	5	4	6	4	4	4	**4**	4	3
	+1K-4KHz	6	5	7	5	6	4	7	**2**	7	4	8	5	5	5
	+4K-8KHz	6	5	6	3	7	5	7	7	5	**3**	5	4	**2**	**2**

Table 3.4.14 The Spearman's correlation results between the evaluated annoyance and loudness of the indirect method test for each subject.

	Correlation Coefficient	**Sig. (2-tailed)**		**Correlation Coefficient**	**Sig. (2-tailed)**
P1	.649	.236	P8	.395	.511
P2	.406	.498	P9	.158	.800
P3	.564	.322	P10	.447	.450
P4	.316	.604	P11	.410	.493
P5	.821	.089	S1	**1.000**	**.000**
P6	.649	.236	S2	-.412	.490
P7	-.530	.358	S3	-.447	.450

The average annoyance and loudness results for LFN sufferers, the reference group and different questionnaire groups were also calculated and compared (Figure 3.4.9 and Figure 3.4.10). The obvious annoyance difference was only found between LFN sufferers and the reference group. So the annoyance value of S1, S2 and S3 were almost the same for LFN sufferers, but an increased trend was found for the reference group. The difference between the other groups was minor and the changings were in the similar trends that the annoyance increased when the frequency range of additional bandwidths PNs rose. The changing trends of loudness assessment were similar between groups. The very low loudness value of S5 (LFN+4K-8K Hz) in some groups was supposed due to the hearing deficiency at high frequency range for LFN sufferers.

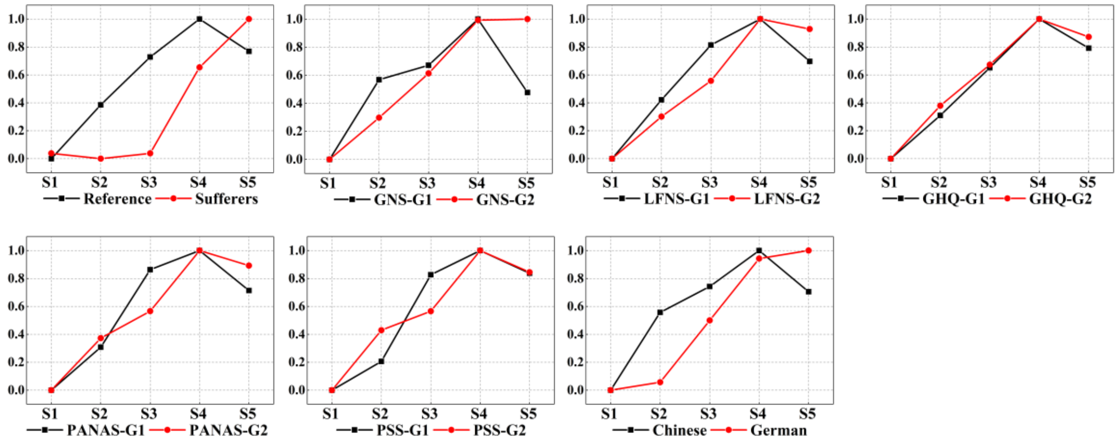


Figure 3.4.9 The comparison of annoyance results of the indirect method test between subjects groups and between questionnaire groups

(X axis - test signals: S1 (LFN), S2 (LFN+250-500 Hz), S3 (LFN+500-1K Hz), S4 (LFN+1K-4K Hz), S5 (LFN+4K-8K Hz); Y axis - SAV level of pair-wise comparison method)

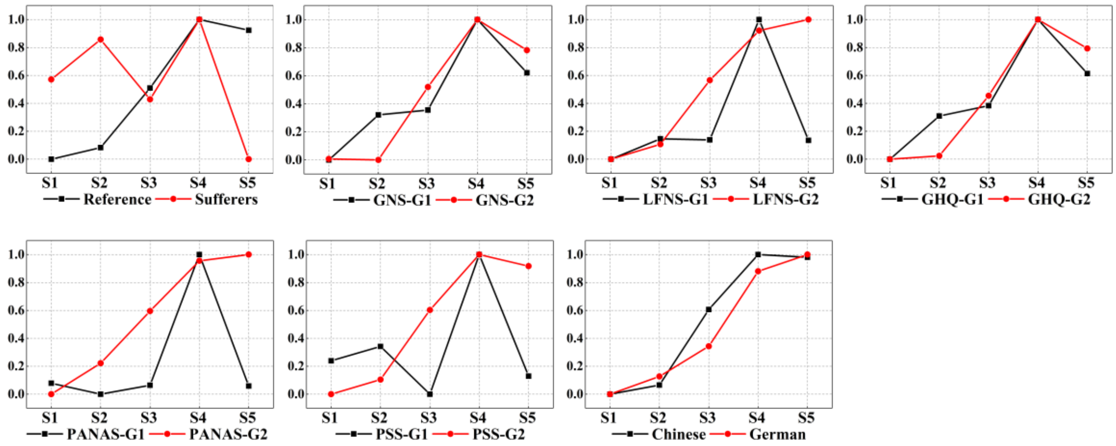


Figure 3.4.10 The comparison of loudness results of the indirect method test between subjects groups and between questionnaire groups

X axis - the same signal arrangement as in Figure 3.4.9; Y axis - loudness level of pair-wise compassion method)

- **The results of the final subjective evaluation listening test**

During the EEG measurement the subjects listened to the four noise signals each for 2 minutes, which meant that they were already familiar with these signals, so it was supposed that they could give a more accurate judgment of annoyance and loudness for the signals, and the high repeated reliability result supported this concept. Therefore, the results of the final subjective evaluation listening test were used to compare with the objective results obtained from the EEG measurement stage.

Table 3.4.15 depicts the SAV and loudness (both range from 1 to 11) results for all subjects. The LFN and PN were the same for all subjects. But for each subject the frequency of added PT was the marked maximum SAV result in Table 3.4.11, and the frequency range of added PN was the marked minimum SAV result in Table 3.4.13. Table 3.4.16 is the correlation results between SAV and loudness. 36% of the correlation results between SAV and loudness were significant.

The average and SD values of SAV and loudness were calculated, which represented the evaluation range for each subject (Figure 3.4.11). Figure 3.4.12 is the SAV and loudness distribution of LFN for all subjects. Considering the evaluation range (1-11) the subjects could be classified into three levels. LFN sufferers gave a relative higher annoyance assessment on LFN than the reference group, but there were no obvious loudness evaluation results between two groups.

Table 3.4.15 The SAV and loudness (both range from 1 to 11) results of the final listening test (LFN and PN are the same for all subjects, LFN+PN and LFN+PT are the marked signal combinations for the annoyance result part in Table 3.4.11 and Table 3.4.13 for each subject).

SAV					**Loudness**				
	LFN	LFN+PN	LFN+PT	PN		LFN	LFN+PN	LFN+PT	PN
P1	2.67	2.33	4.00	4.00	P1	3.00	2.67	4.00	4.00
P2	6.00	6.33	7.67	8.67	P2	6.00	6.00	7.67	7.33
P3	6.00	7.00	8.67	5.00	P3	6.00	7.00	7.67	9.67
P4	6.00	6.33	7.00	8.33	P4	4.67	5.33	5.00	8.00
P5	3.67	2.67	8.00	11.00	P5	3.00	2.33	8.00	11.00
P6	2.67	3.00	6.33	10.00	P6	3.00	3.00	6.67	8.00
P7	6.33	7.33	7.67	8.33	P7	5.67	6.67	6.67	8.00
P8	5.00	6.67	7.33	8.67	P8	4.67	6.00	6.67	8.33
P9	2.67	3.00	5.00	8.67	P9	2.67	3.00	4.50	8.00
P10	6.67	6.00	7.67	6.67	P10	5.33	4.67	6.67	6.33
P11	5.00	8.33	8.33	11.00	P11	3.00	6.67	6.33	11.00
S1	8.00	9.33	9.33	5.00	S1	7.00	8.00	8.00	8.33
S2	6.00	5.33	6.00	1.00	S2	4.67	4.33	6.50	3.00
S3	9.33	8.33	10.00	4.00	S3	4.00	3.67	4.33	3.00

Table 3.4.16 The Spearman's correlation results between SAV and loudness of the final listening test for each subject.

	Correlation Coefficient	**Sig. (2-tailed)**		**Correlation Coefficient**	**Sig. (2-tailed)**
P1	**1.000**	**.000**	P8	**1.000**	**.000**
P2	.738	.262	P9	**1.000**	**.000**
P3	-.200	.800	P10	.949	.051
P4	.800	.200	P11	.949	.051
P5	**1.000**	**.000**	S1	-.333	.667
P6	.949	.051	S2	.949	.051
P7	.949	.051	S3	**1.000**	**.000**

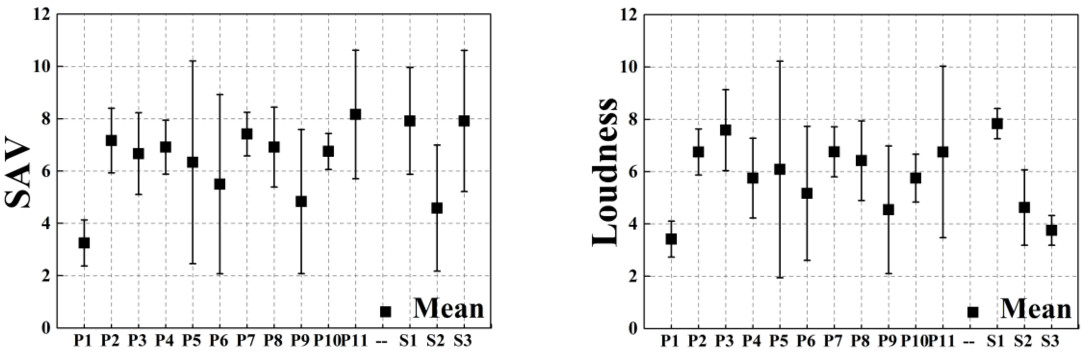


Figure 3.4.11 The mean value and SD of SAV (left) and loudness (right) (both range from 1 to 11) for each subject

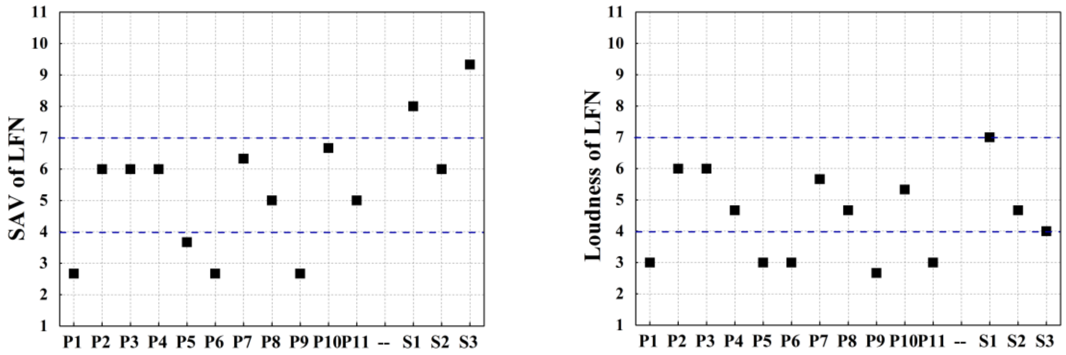


Figure 3.4.12 The distribution of SAV and loudness evaluation results of LFN for all subjects (both range from 1 to 11)

The relative SAV and loudness were calculated to compare the SAV and loudness variation due to the different additional components, which were corresponded to each subject's individual SAV and loudness results of LFN (Figure 3.4.13). For all subjects the SAV of LFN combined with PT was higher than the SAV of LFN. The relation between the SAV of LFN combined with PN and the SAV of LFN was not consistent. The SAV results of LFN combined with PN were all around the result of LFN. For the reference group 27% of the subjects felt the annoyance of LFN combined with PN to be lower than the individual SAV of LFN, and the result for the LFN sufferers was 67%. Notable, all LFN sufferers evaluated the SAV of PN lower than that of LFN and the subjects in the reference group assessed PN more annoying than the other signals.

The overall structure of the loudness result was similar to the SAV result. The loudness of LFN combined with PT and the loudness of PN were all higher than the value of LFN for the reference group. All the findings indicated that adding PTs in the low frequency ranges with LFN could cause the tonal effect and increase the annoyance and loudness. Adding bandwidth PNs in the middle or high frequency ranges could change the annoyance and loudness but the effect was individual, which meant that the indirect method might be not suitable for everyone. PN was evaluated louder and more annoying than LFN with the same level for subjects belonging to the reference group, but the result was opposite for LFN sufferers.

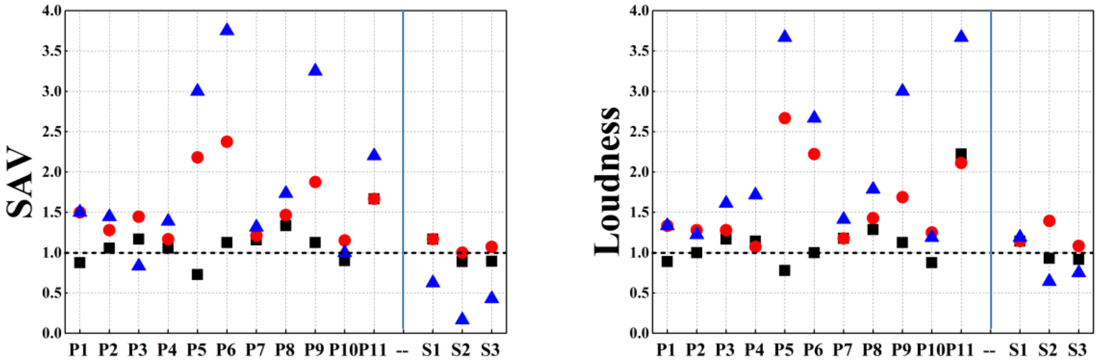


Figure 3.4.13 The relative SAV and loudness results compared to the result of LFN

■ LFN+PN ● LFN+PT ▲ PN

Figure 3.4.14 shows the SAV and loudness results compared between groups. As mentioned above, the SAV changing trend for LFN sufferers was the same for LFN, LFN+PT and LFN+PN as the reference group, but the value for LFN sufferers was higher. The similar SAV results were also found for the LFNS and GHQ groups. But the loudness results for them had no obvious difference. It was almost the same between GNS groups. Although the loudness variation trends for PANAS and PSS groups were similar, the value for PANAS-G2 was higher than that for PANAS-G1, and also the PSS-G2 got a higher loudness result.

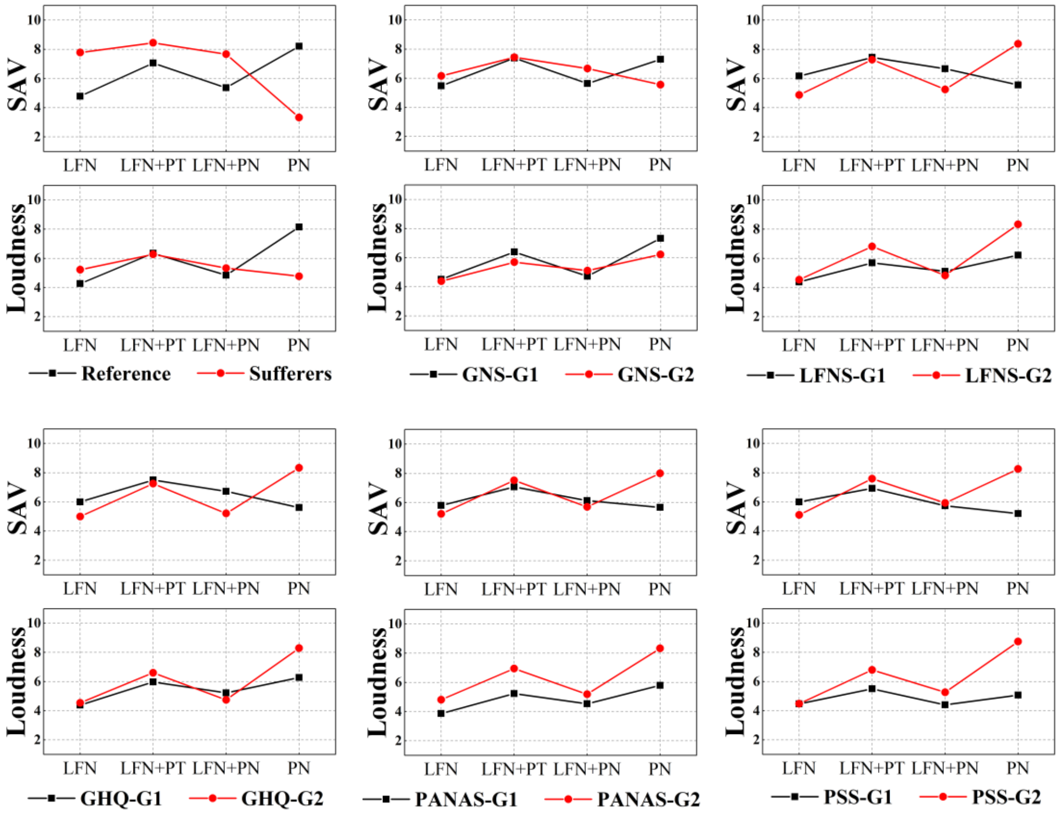


Figure 3.4.14 The comparison of SAV and loudness (both range from 1 to 11) results of the final listening test between subjects and between questionnaire groups

(X axis - LFN, LFN+PT, LFN+PN, PN (the frequency of PT and the frequency range of PN is individual and is the marked signal in Table 3.4.11 and Table 3.4.13); Y axis - SAV and loudness result (both range from 1 to 11)

3.4.3.3 The results of EEG recording

The EEG measurement data were edited into the same length of each signal segment firstly, and then artifacts were removed with ICA calculation in EEGLAB. Due to the same reason as described in other EEG processes, RPSD based on the PSD of the "Pre" stage was calculated and used for the further analysis. To compare the brain reaction under different noise exposures, the average PRSD relative to the PSD of LFN was calculated. Figure 3.4.15 illustrates the average RPSD relative to the PSD of LFN for the reference group and LFN sufferers. There was almost the same between two groups for α and α2 result, but for the other EEG bands there were obvious differences.

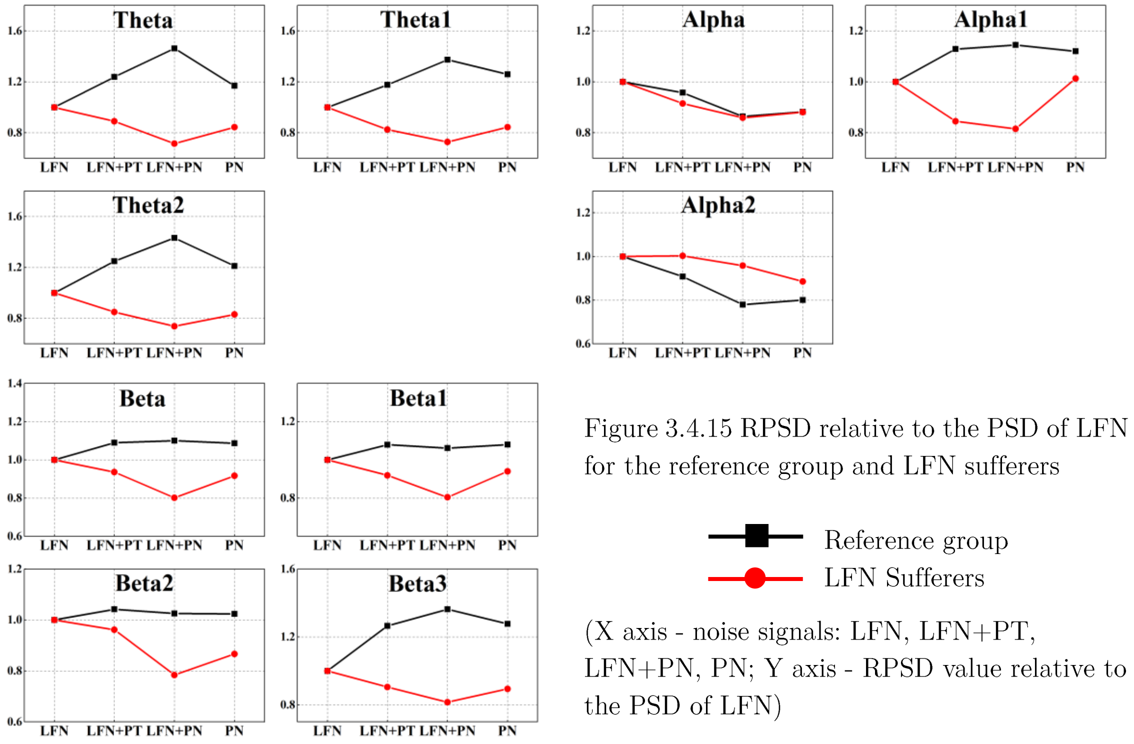


Figure 3.4.15 RPSD relative to the PSD of LFN for the reference group and LFN sufferers

(X axis - noise signals: LFN, LFN+PT, LFN+PN, PN; Y axis - RPSD value relative to the PSD of LFN)

The EEG reactions over time to different stimuli were calculated with epoch of every 10 seconds. Figure 3.4.16 and Figure 3.4.17 are the PSD results relative to D1 (the PSD of the first 10 second EEG data) of the reference group and LFN sufferers. The two obvious peaks of the PSD curves were pointed and the time intervals for “Pre” and for the other EEG stages under noise exposures were named as t1 to t5. There were obvious differences between two groups in the “Pre” part. For the reference group the PSD curves of four brain function areas for θ and α band were in an increasing trend and for β band were almost the same, but for LFN sufferers there was no significant changing trend. The results in the “LFN” part for both groups were similar, but the appearing time of the first peak for LFN sufferers was later than the reference group, and the time of the stable PSD for α band appeared later for LFN sufferers than for the reference group. The PSD changing of θ and β band in the “LFN +PT” and “LFN +PN” stages were highly consistent for the reference group, but the curves of α band were different between different lobes. The results for θ and β band in these two stages for LFN sufferers showed stronger variation between lobes, and for α band in the “LFN+PN” part was more consistent than the reference group. The PSD variation under PN exposure for the reference group was similar as under the exposure of LFN+PT, t3 and t5 appeared later than t2 and t5 for β band. The beginning part of the PSD results for different lobes showed different changing trends for LFN sufferers in this stage, but the variations were similar at the end.

In general, there were different PSD changing trends between LFN sufferers and the reference group under the same noise exposure. And the consistencies between different brain areas were also different for two subject groups. It was supposed that the appearing time of the relative stable PSD for α band had a relation with the duration of the annoyance caused by LFN, and the later appearing time for LFN sufferer supported this hypothesis.

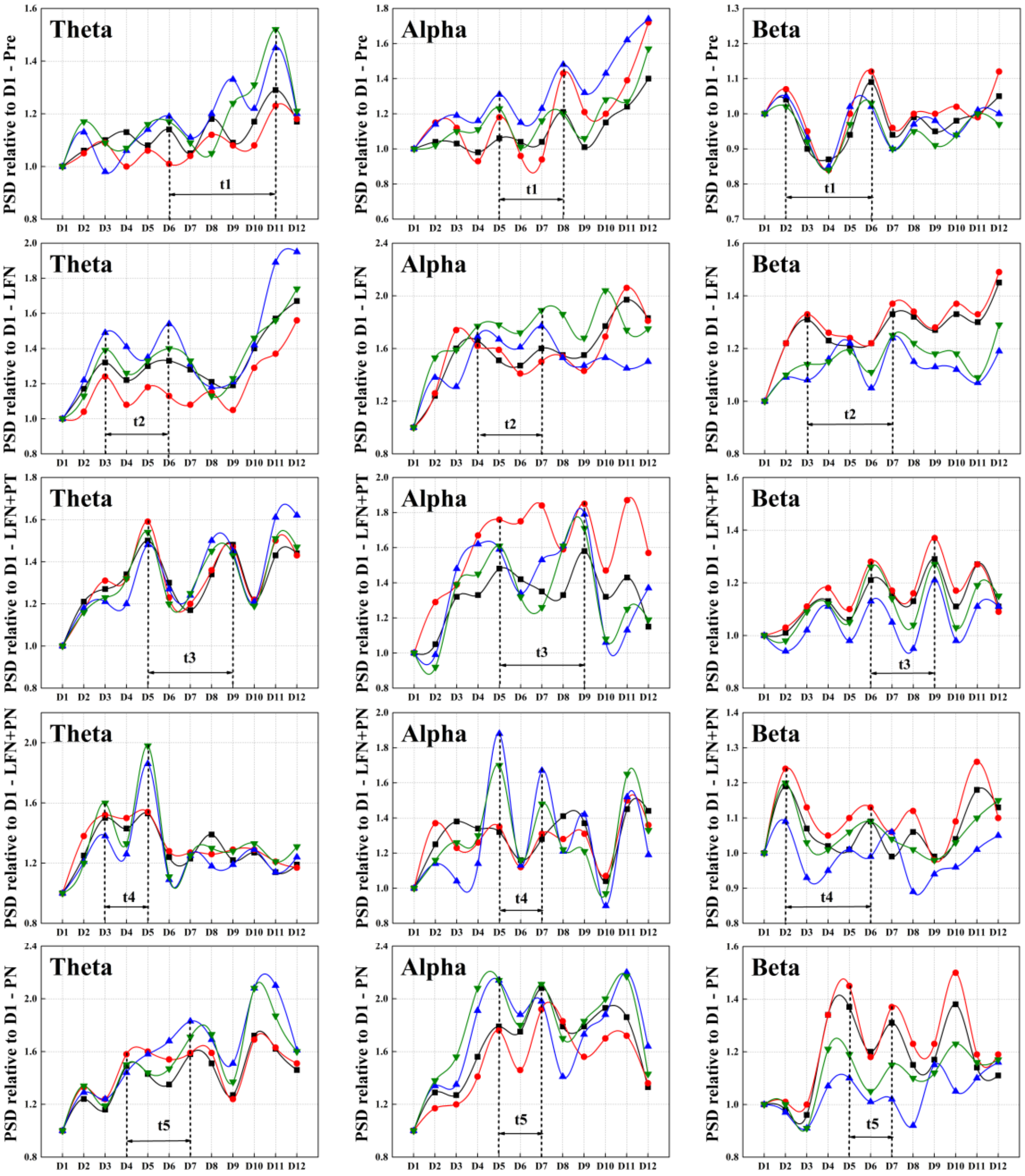


Figure 3.4.16 The results of PSD relative to D1 in different stages for the reference group

■ C ● F ▲ P&O ▼ T

(four function areas: C-central, F-frontal, P&O parietal and occipital, T-temporal)(X axis - D1 to D12 (each is 10s EEG data); Y axis - PSD relative to D1 (the first 10s EEG data))

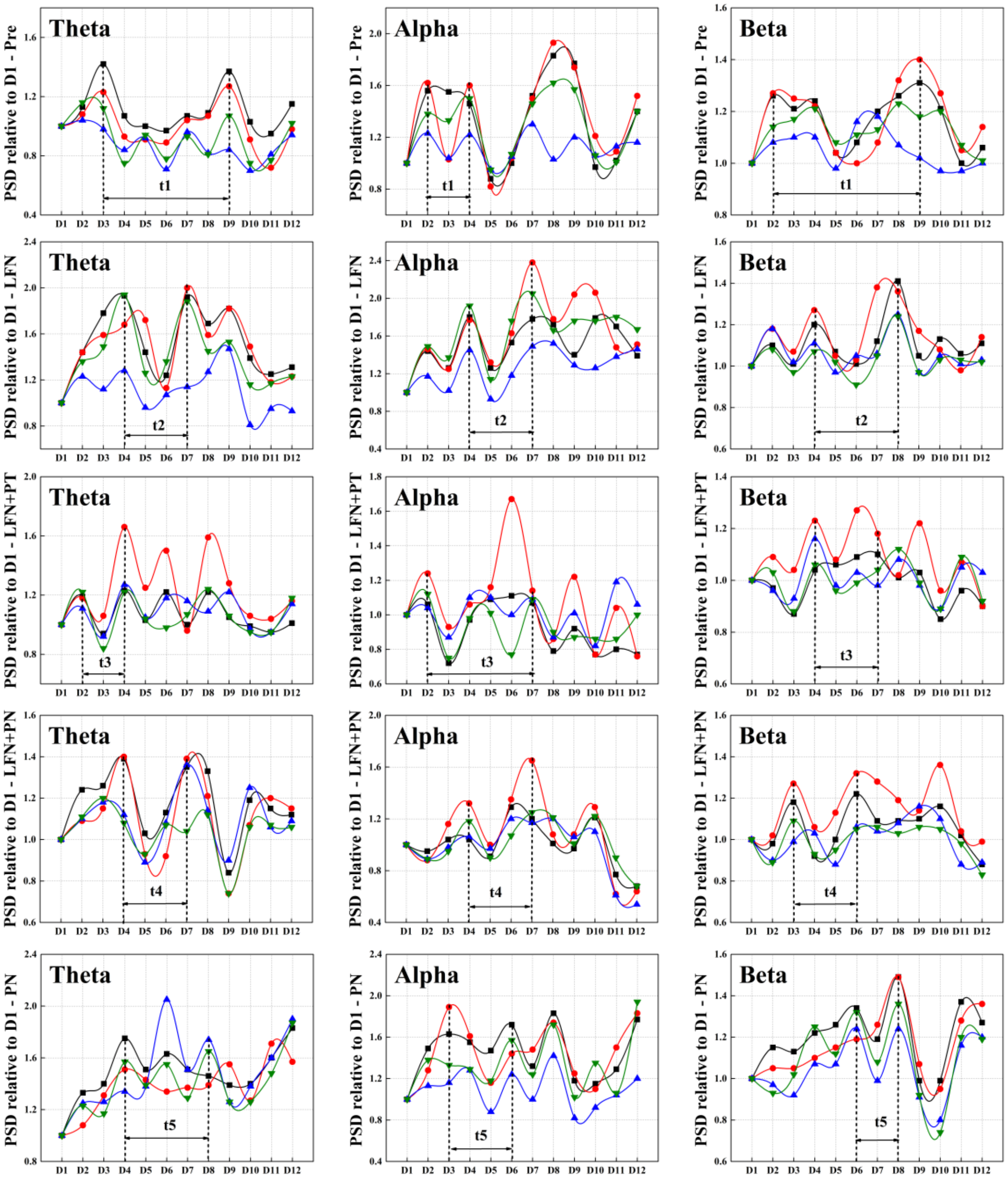


Figure 3.4.17 The results of PSD relative to D1 in different stages for LFN sufferers

■ C ● F ▲ P&O ▼ T

(X axis - D1 to D12 (each is 10s EEG data); Y axis - PSD relative to D1 (the first 10s EEG data))

The RPSD of all stages were calculated with Homogeneity of variances and ANOVA in SPSS to check the difference between the groups. The significant results are summarized in Table 3.4.17, which indicated that there were different EEG changes for subjects with different personality traits. Especially the significant differences were found in all EEG bands between LFN sufferers and the reference group.

Table 3.4.17 The comparison of RPSD between groups (* means Homogeneity > 0.05 and ANOVA ≤ 0.05, A - average PSD result of all electrode positions; C, F, PO, T - average PSD results in central, frontal, parietal & occipital and temporal area).

		RS	GNS	LFNS	GHQ	PANAS	PSS			RS	GNS	LFNS	GHQ	PANAS	PSS
α	A	*		*				**α1**	A	*	*	*	*	*	*
	C	*		*	*	*	*		C	*	*	*	*	*	*
	F	*		*			*		F	*	*	*	*	*	*
	PO								PO	*	*	*	*		
	T	*							T			*	*	*	*
α2	A	*					*	**β**	A	*		*		*	*
	C	*					*		C					*	*
	F	*			*		*		F	*		*			
	PO								PO		*				
	T	*					*		T		*	*			
β1	A	*		*	*	*	*	**β2**	A					*	
	C	*			*	*	*		C	*				*	*
	F	*	*	*	*	*	*		F						
	PO		*						PO		*				
	T		*						T						
β3	A							**θ**	A	*					
	C								C	*					
	F								F						
	PO			*					PO	*		*	*		
	T	*							T	*					
θ1	A							**θ2**	A	*		*			
	C	*							C	*					
	F								F						
	PO								PO			*	*	*	
	T								T	*			*		*

3.4.3.4 The correlation results between EEG and SAV

The relationships between RPSD and SAV, and RPSD and loudness were calculated for each subject. Figure 3.4.18 and 3.4.19 are the comparison results, which show the proportion of the significant relationships. The results distinguished different brain function areas. The correlation results between RPSD and SAV for θ group bands were mostly positive and found mostly in the frontal, temporal and occipital areas which agreed with the early result from experiment 3.2 and other's findings that increased θ band might accompany both cognitive and emotional activation. The relations between RPSD of α group bands and SAV were inconsistent that there were positive and negative correlations even for the same electrode position. But more positive results for α1 were found in the frontal area, and for α2 the negative relation was dominant. The RPSD of β group bands at the temporal area had negative correlations with SAV, which were also found in the experiment 3.2. But the relation for the frontal area was positive for β1 and negative for β2. The correlation results between loudness and RPSD of θ group bands were also in positive, which was similar as the result for SAV. But more negative correlation results were found between loudness and RPSD of α, α2. And the negative correlation was dominant for β group bands.

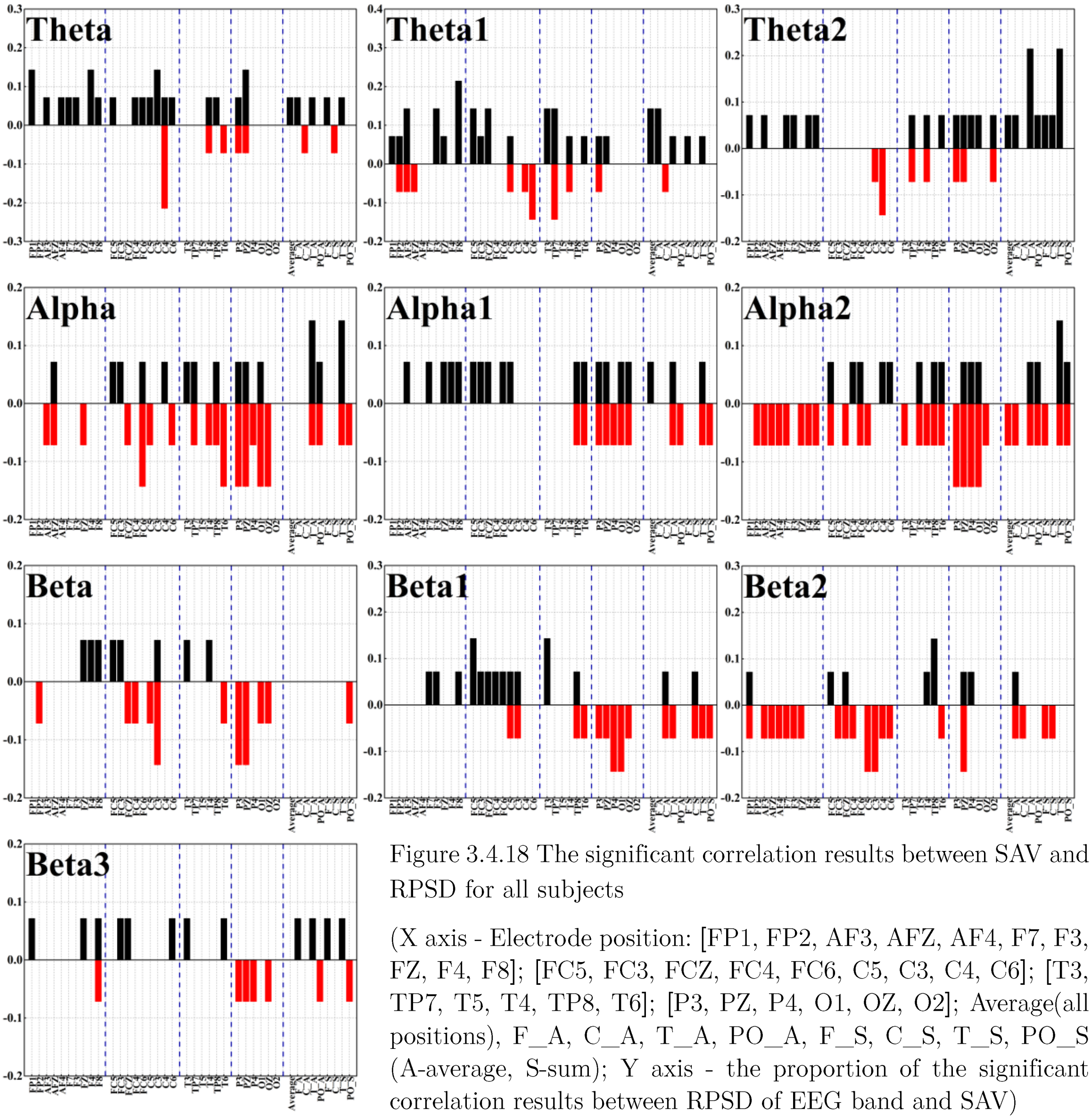


Figure 3.4.18 The significant correlation results between SAV and RPSD for all subjects

(X axis - Electrode position: [FP1, FP2, AF3, AFZ, AF4, F7, F3, FZ, F4, F8]; [FC5, FC3, FCZ, FC4, FC6, C5, C3, C4, C6]; [T3, TP7, T5, T4, TP8, T6]; [P3, PZ, P4, O1, OZ, O2]; Average(all positions), F_A, C_A, T_A, PO_A, F_S, C_S, T_S, PO_S (A-average, S-sum); Y axis - the proportion of the significant correlation results between RPSD of EEG band and SAV)

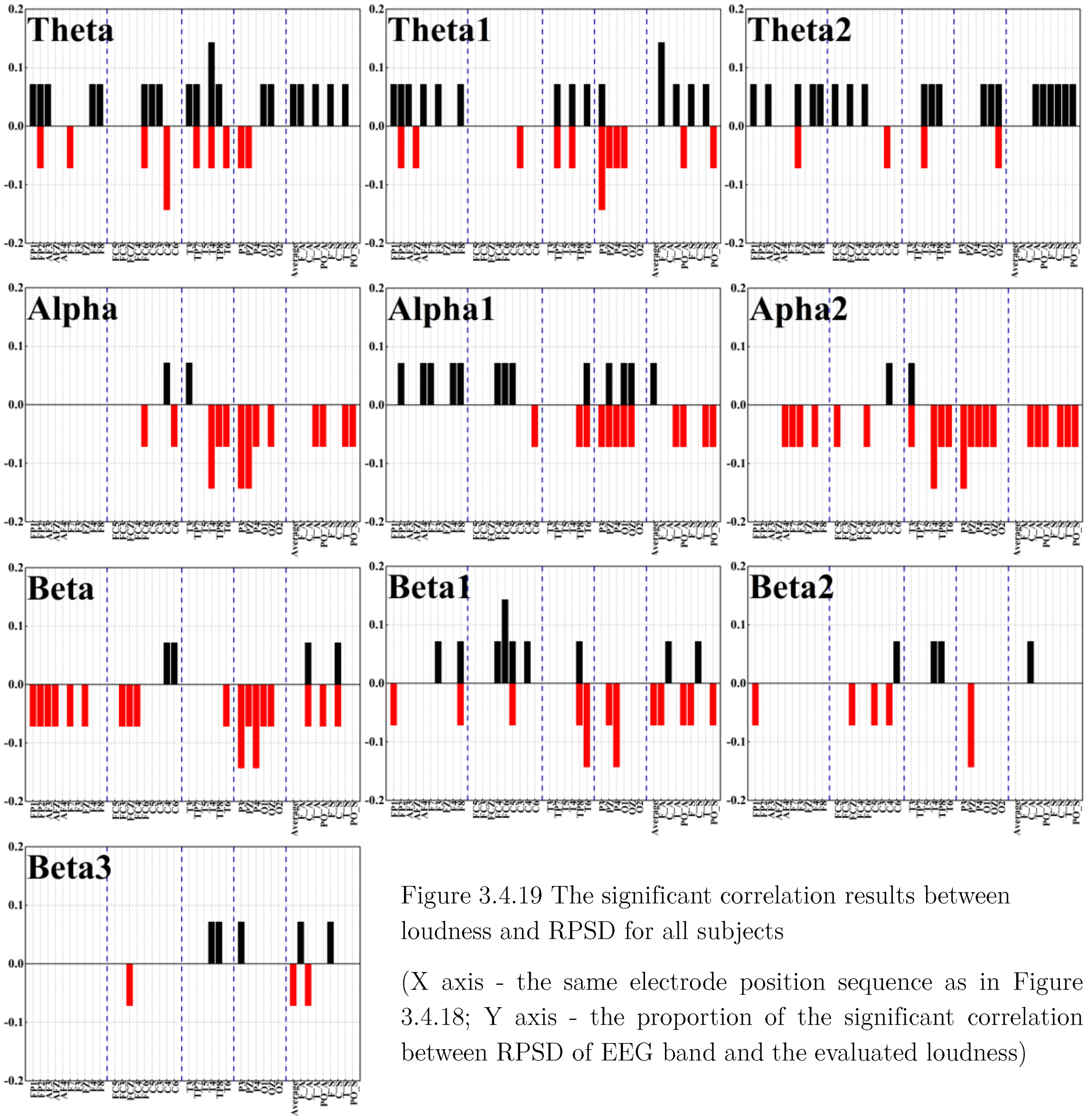


Figure 3.4.19 The significant correlation results between loudness and RPSD for all subjects

(X axis - the same electrode position sequence as in Figure 3.4.18; Y axis - the proportion of the significant correlation between RPSD of EEG band and the evaluated loudness)

The correlation calculations between subjective evaluation results and EEG measurement results were also compared between different groups. Figure 3.4.20 displays the comparison results between LFN sufferers and the reference group. There were obvious different correlation relations for two subject groups. For example, the positive relations between RPSD of θ and θ1 band were dominant for the reference group but more negative results were found for LFN sufferers. There were more positive correlations between RPSD of α bands and SAV for LFN sufferers, and more negative results for the reference group especially at the temporal, occipital and parietal areas. The results for β bands showed no obvious difference. The correlations between loudness and RPSD at most of the EEG bands for LFN sufferers were weak, only β2 showed negative correlation. In the same time, the strong positive correlation for loudness with the RPSD of ϴ band, and a negative relation with α band were found for the reference group.

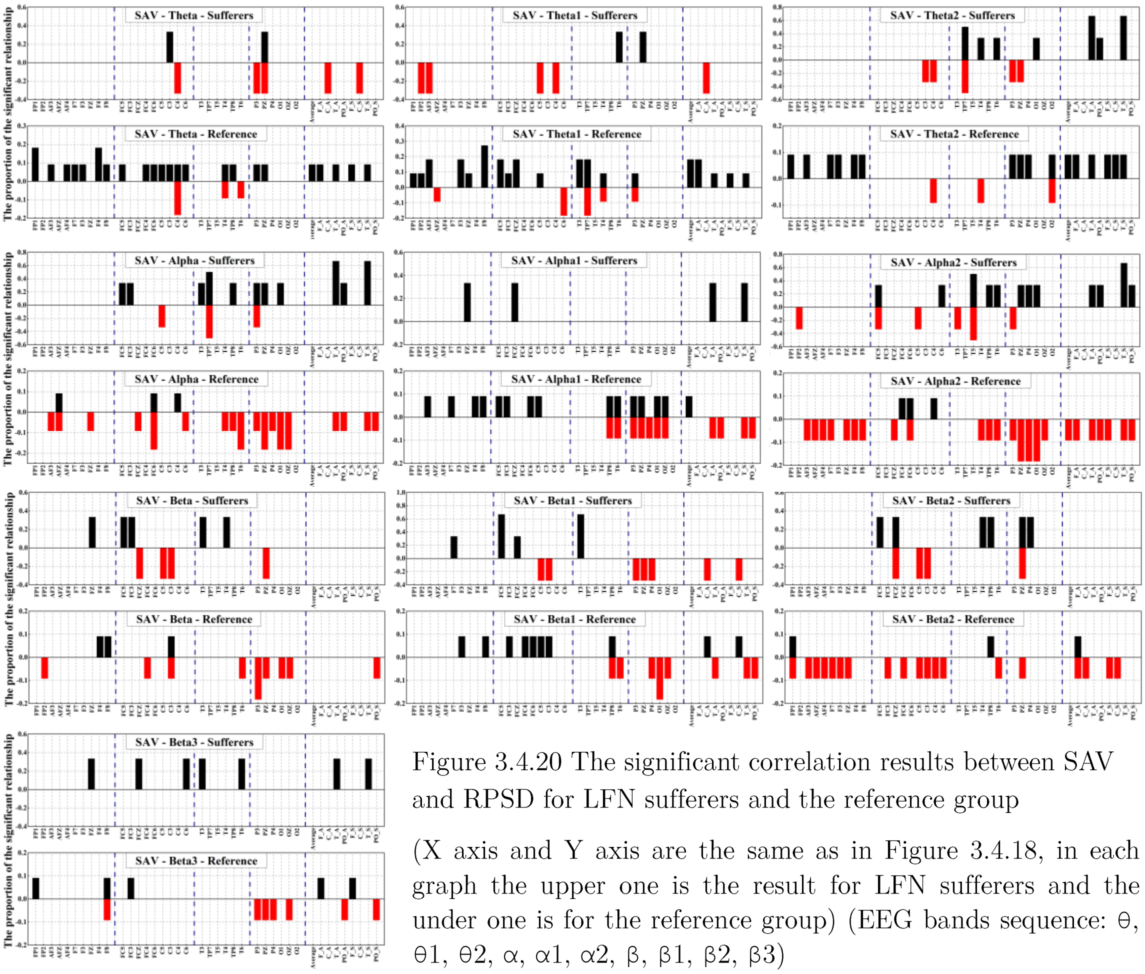


Figure 3.4.20 The significant correlation results between SAV and RPSD for LFN sufferers and the reference group

(X axis and Y axis are the same as in Figure 3.4.18, in each graph the upper one is the result for LFN sufferers and the under one is for the reference group) (EEG bands sequence: ϴ, ϴ1, ϴ2, α, α1, α2, β, β1, β2, β3)

The other comparison results for GNS, LFNS, GHQ, PANAS and PSS groups are in Appendix 2.2. The different correlation results between subjects with different personality traits were not as significant as the results for LFN sufferers and the reference group, but there were still some findings. For example, the negative relations were dominant between SAV and RPSD of α band for LFNS-G2, and also for GNS-G2 and GHQ-G2. The results for LFNS-G1, GNS-G1 and GHQ-G1 were both negative and positive. There was a strong positive correlation between SAV and RPSD of ϴ band for PSS-G2, but for PSS-G1 the relation was weak. The results between RPSD and loudness didn't show obvious differences between groups, only some strong positive relations were found for GHQ-G1 but for GHQ-G2 the correlation was weak. For PANAS-G1 the negative correlation was dominant.

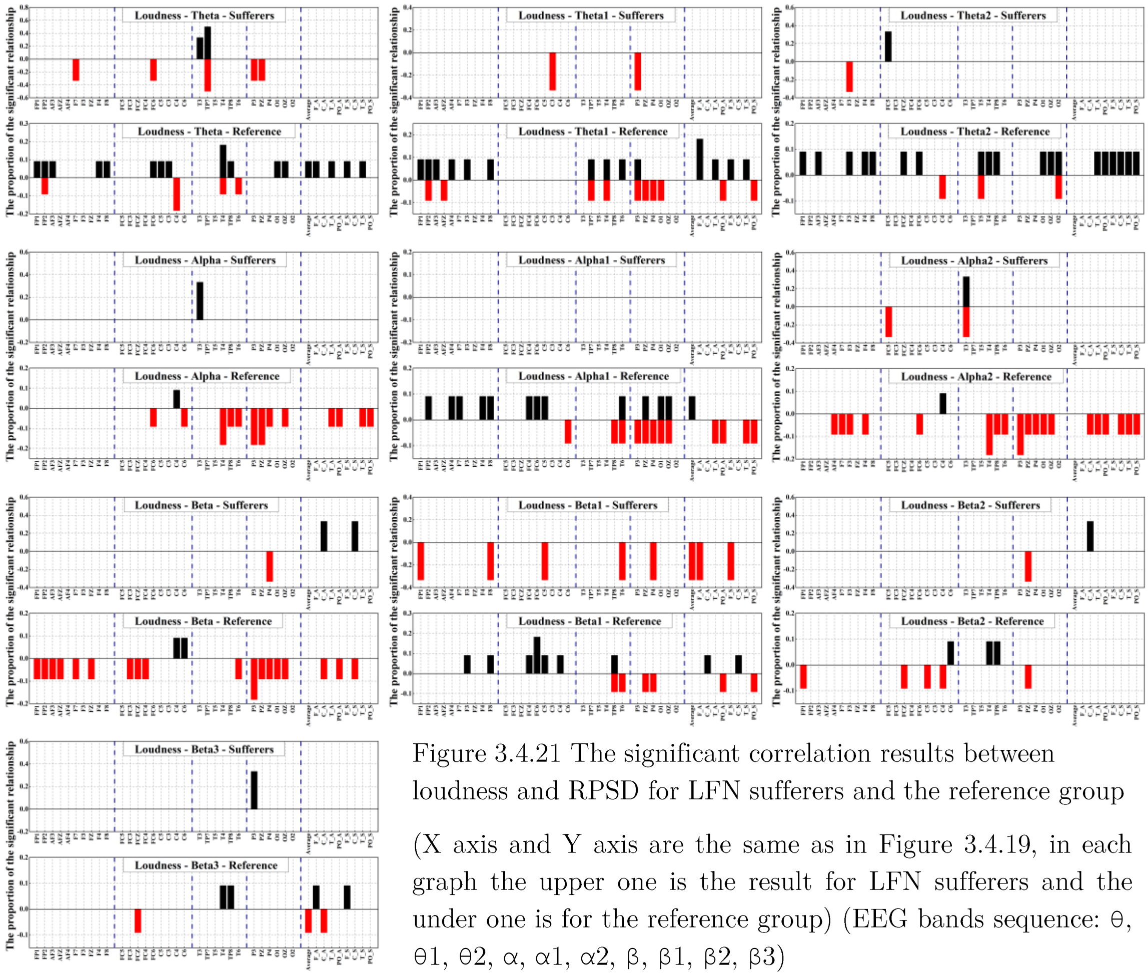


Figure 3.4.21 The significant correlation results between loudness and RPSD for LFN sufferers and the reference group

(X axis and Y axis are the same as in Figure 3.4.19, in each graph the upper one is the result for LFN sufferers and the under one is for the reference group) (EEG bands sequence: θ, θ1, θ2, α, α1, α2, β, β1, β2, β3)

The findings of all listening tests, EEG measurement data and the relations between subjective and objective parameters were summarized as follows:

- All LFN sufferers had high sensitivity for LFN with no doubt, but only one of three subjects got high scores for GNS, which indicated that LFN sufferers could be very sensitive to LFN but with normal sensitivity for general noise. And they got high GHQ and PSS scores, which showed their relative poor mental performance and high stress situation.
- The relative hearing threshold test showed that the hearing ability of LFN sufferers at low frequency ranges was no difference compared with the reference subjects and had a normal level. But they had deficiency at high frequency ranges, which could cause their different annoyance and loudness assessment results for LFN combined with PT or PN.
- There were obvious different annoyance evaluation results between LFN sufferers and the reference group in the low frequency sensitivity test when LFN was combined with 63, 80 and 100 Hz PT. The annoyance value for the reference group was increased with rising frequency, which meant that extra PT could cause additional annoyance for them. But the

annoyance value for LFN sufferers was in an opposite changing trend. The annoyance value was decreased with increasing frequency, which could be possible because of their special sensation to low frequency range or due to the spectrum balance effect that the added PT was near the energy attenuated frequency of LFN. These findings suggested that the tonal character of LFN could worsen the subjective feelings for normal people, but for LFN sufferers the effect could be different.

- The annoyance reducing effect was not significant in the indirect method test. The reduced annoyance value, due to the additional PN in middle or high frequency range, was only found for some subjects but not for all. There was also no obvious difference between groups, only for LFN sufferers. Because their annoying feeling was found lower than that of the original LFN when PN in frequency range of 250 - 500 Hz was added to LFN. The loudness results of both subjective evaluation listening tests didn't show a strong difference between groups. The only obvious difference was the low loudness value of LFN combined with PN in frequency range of 4K-8K Hz for LFN sufferers and for LFNS-G1, PANAS-G1 and PSS-G1 which included LFN sufferers. This difference was supposed due to LFN sufferers' deficient hearing ability at high frequency ranges, which reduced the effect of the added PN. And there were found no significant different annoyance and loudness assessment results between Chinese and German subjects in both listening tests.
- The results of the last listening test indicated that LFN sufferers gave higher SAV (range from 1 to 11) than the reference group, but their loudness assessment (range from 1 to 11) was similar. LFN sufferers considered PN less annoying than LFN, but the reference group gave higher SAV for PN than for LFN. The SAV of LFN combined with PT was much higher than the value of LFN for the reference group, but the SAV of both stimuli were similar for LFN sufferers. The SAV of LFN combined with PN was found around that of LFN for all subjects, which confirmed the obtained conclusion that the indirect method could have a certain effect to reduce the annoyance caused by LFN. And it could be more suitable for subjects belonging to GHQ-G1 and PSS-G2, who had a relative poor mental performance and lower stress, which was agreed with the result from experiment 3.3.
- EEG data confirmed the different brain reactions to the same LFN and other signals among subjects. The significant different RPSD results between LFN sufferers and the reference group for all EEG bands were obtained from the ANOVA calculation. The significant results were also found for subjects belonging to different questionnaire groups, which indicated the certainly of distinction due to the different personality traits.
- The changing of PSD over time was individual in different brain function areas under different noise exposures. Although the NMDS results showed that the distance among the reference group was near and relative far from LFN sufferers, there were too many other uncontrollable and unclear aspects which could affect this parameter.
- The correlation results between SAV and EEG data were agreed with the findings from

experiment 3.2 and 3.3. The relations between the average SAV and RPSD of θ band were mainly positive over the head. For β band the significant correlation was negative at the temporal area. The result between SAV and RPSD of α band was insistent that both a positive and negative correlation appeared. The relationship between loudness and RPSD of θ band was also positive, and the result was negative for loudness with RPSD of α and α2.

- The correlation results for SAV and loudness with RPSD were obviously different between LFN sufferers and the reference group. The relation between SAV and RPSD of θ band was in opposite for two groups in that way that it was negative for LFN sufferers and positive for the reference group. Similarly, the correlation was positive between SAV and RPSD of α band at temporal, occipital, and parietal areas for LFN sufferers and was negative for the reference group. Different relations were also found between different questionnaire groups, which were not so obvious but still confirmed the important effect of the different personality traits for the LFN research again.

3.5 The brain variation caused by LFN combined with visual stimuli

The EEG observations in the experiment 3.2, 3.3 and 3.4 were under the situation that there were only auditory stimuli involved and the subjects' eyes were closed. Therefore, it was interesting to investigate whether other sensory stimuli, for example, visual information could affect the perception of LFN, and whether the relation between objective and subjective parameters would be consistent. In this section, the visual effect for the perception and reaction on wind turbine noise (WTN) was investigated, and EEG was measured to observe the relation between brain variation and the annoyance caused by the visual and auditory stimuli from WT.

The sources of noise from wind turbines (WTs) were first identified in the 1980's. Since the levels of produced infrasound at typical residential set-back distances were most likely too low to be audible, WTN was considered as LFN indoors. Compared with other environmental noise sources (road, rail and aircraft noise), annoyance due to WTN was found at lower exposure levels and could be enhanced by WT visibility (Pedersen and Larsman, 2008; VandenBerg et al., 2008) and sound quality issues (Pedersen and Waye, 2004; Pedersen et al., 2009) such as amplitude modulation, intermittency, and the presence of the WTN at night. Among the factors which could affect the annoyance caused by WTN, visual aspects showed an important effect on the overall impression and evaluation to the WTs, which was also special for WTN compared with other LFN sources. For example, people who felt that the WTs would have a negative visual effect on the landscape and thought that the turbines would decrease the recreational value, were more likely to oppose WTs (Johansson and Laike, 2007). Seeing one or more WTs increased not just the possibility of perceiving the sound, but also the possibility of being annoyed. This multimodal effect of the audible and visual exposure from the same source could lead to an enhancement of the negative evaluation of the noise by the visual stimuli (Pedersen and Persson, 2007).

However, most of the investigations were field questionnaire surveys, which didn't show a precise relationship between the visual aspect and subjective annoyance due to WTs. For the other noise situations, the visual attitude towards the noise source was studied more (Pedersen and Larsman, 2008). The loudness of the noise transmitting through barriers of different solidity was compared, and it was judged to be lower with a barrier partially obscuring the sound source than without a barrier, but greater when the sound source was totally obscured (Aylor, 1976). When a visually attractive street was presented together with traffic noise, the evaluated annoyance was lower than the same noise level with a visually unattractive street (Kastka and Hangartner, 1986). The same tendency was found in an experimental study where subjects evaluated the stimuli combined with five visual settings of varying degrees of urbanization and eight urban sounds (Viollon et al., 2002). For both traffic noise and natural sounds like bird song, the more urbanized the visual stimulus, the more negative were the sound ratings.

In addition, the individual factors were found having certain influence on annoyance from WTN. For example, psychological distress assessment with the GHQ-12 in a WTN study showed that although the direct relation between noise level and psychological distress was not significant, the annoyance and sleep disturbance caused by the WTN rather than the noise itself may lead to the distress (Bakker et al., 2012).

3.5.1 Subjects and experimental material

Six-teen students (8 males and 8 females) from the University of Wuppertal were recruited as subjects in the experiment. According to the measurement result of 29 WTs in Japan (Tachibana et al., 2014), all WTs showed similar spectral characteristics, which could be approximated by a -4 dB/octave slope in band spectrum. Therefore, the WTN used in the test was generated with the same spectral form, which was White Noise through low pass filter (cut frequency 20 Hz and order 1). The level of the stimulus was set to 40 dBA, which was used as a limitation in several national standards (Bowdler and Leventhall, 2014). Generally, WTN has a special shape in time domain which could affect the subjective feelings, but the influence of this character of WTN was not considered in the light of the purpose and emphases of this test.

The visual signals were field recordings in Zetel of Lower Saxony in Germany. Figure 3.5.1 shows the screenshots of the visual signals. The types of the WTs were Vestas 110 and Enercon E-66. The distance between the recording location and the WT was around 300m. There were three baseline signals (B1 to B3) and eight test signals (S1 to S8), which contained the same WTN and different visual stimuli (Table 3.5.1). Considering the types of the WTs and the limitation of the visual recordings, the high blade rotating speed was set to 15 rpm (rpm= revolutions per minute), normal speed as 10 rpm, and low speed as 7.5 rpm. Different blade rotating speeds of WT (Signal 1, 3, 5) and WT without rotating (Signal 8) were renamed as Signal-Group1 (SG1), and WT with different landscapes (Signal 2, 4, 6) and signal contained several WTs (Signal 7) renamed as Signal-Group2 (SG2).

Table 3.5.1 The signal arrangement of the WTN test. (S-slow blade rotating speed; N-normal speed; F-fast speed).

Signal	auditory stimulus	visual stimulus	Signal	auditory stimulus	visual stimulus
B1	no	no	**S4**	WTN	WT with several cows (N)
B2	WTN	no	**S5**	WTN	WT (N)
B3	no	WT (N)	**S6**	WTN	WT in 90° direction (N)
S1	WTN	WT (S)	**S7**	WTN	Several WTs
S2	WTN	WT hidden by trees (N)	**S8**	WTN	WT without rotating
S3	WTN	WT (F)			

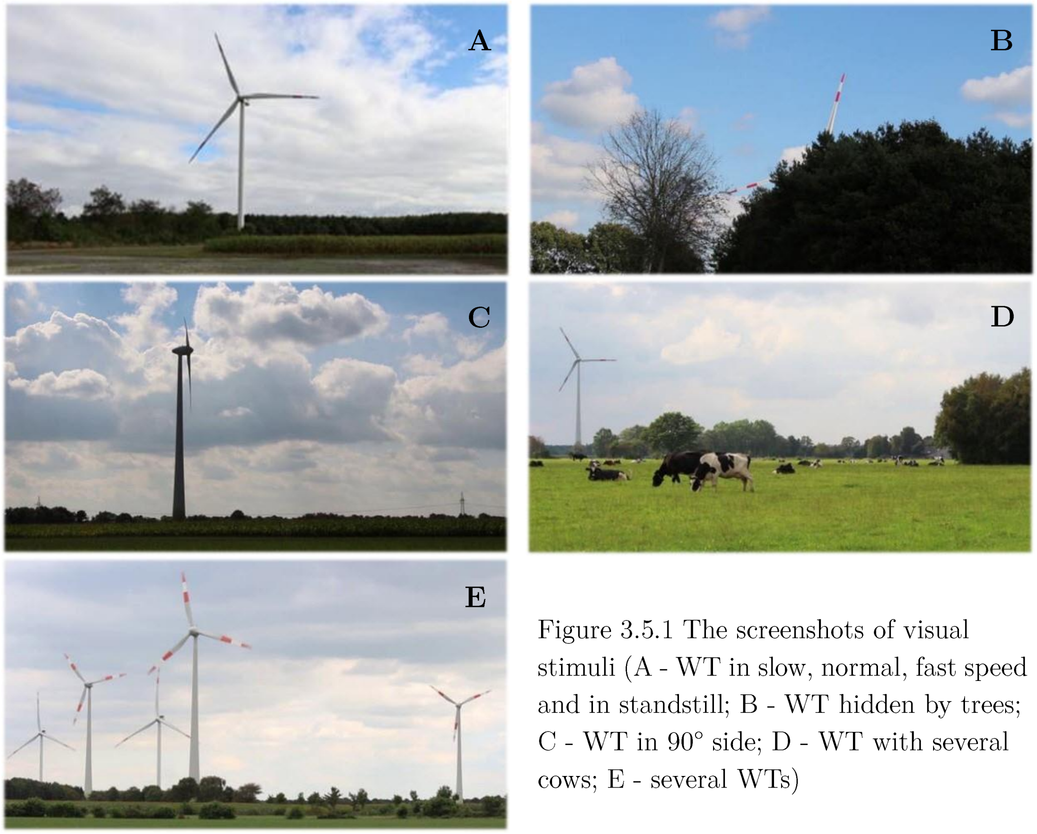


Figure 3.5.1 The screenshots of visual stimuli (A - WT in slow, normal, fast speed and in standstill; B - WT hidden by trees; C - WT in 90° side; D - WT with several cows; E - several WTs)

3.5.2 Experiment method and procedure

Firstly, the subjects answered several questionnaires before the test, which included L/R handedness, HP, GNS, GHQ, and PANAS. They also showed their attitude to WT (Table 3.5.2). Then they sat in front of a monitor and two loudspeakers with a 1.5 m distance. They were asked to face the monitor and try to keep still. The light in the chamber was turned off. The order of the signals was from B1 to B3 then followed by Signal 1 to 8. The duration for baseline and each test signal was 1 min, and between each signal there was a 30 s pause, showing a gray screen and in silence. In the pause the subjects were asked to assess the annoyance level to the previous signal (except B1) in a five evaluation criterion (“1” for not annoying at all and “5” for very annoying). The brain reaction was observed with Neuro-Spectrum-5. The chosen electrode positions were AF3, AF4, T3, T4, O1 and O2, with CZ as the reference position, EOG at left and right sides were also recorded.

Table 3.5.2 The attitude towards WT questionnaire (**AT**).

<table>
<tr><td>1</td><td colspan="2">very positive</td><td></td><td colspan="3" rowspan="5">What is your opinion on the impact of wind turbines on the landscape scenery (AT1)</td></tr>
<tr><td>2</td><td colspan="2">positive</td><td></td></tr>
<tr><td>3</td><td colspan="2">neither positive nor negative</td><td></td></tr>
<tr><td>4</td><td colspan="2">negative</td><td></td></tr>
<tr><td>5</td><td colspan="2">very negative</td><td></td></tr>
<tr><td colspan="2">What is your opinion on the statements below about wind turbines?</td><td>(A) environmentally friendly or impacting</td><td>(B) pretty or ugly</td><td>(C) necessary or unnecessary</td><td>(D) natural or unnatural</td><td>(E) safe or dangerous</td></tr>
<tr><td>1</td><td>very agree with the positive description</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>a little agree with the positive description</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>neutral</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>a little agree with the negative description</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>very agree with the negative description</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

3.5.3 Data analysis

The results of used questionnaires were summarized in Table 3.5.3. Because one subject - P10 gave the same SAV to all the signals, his result was removed from further analysis. And considering the possible effect of the handedness on the EEG result, the result of P15 with left handedness was also eliminated, which meant that the results of 14 subjects were left and used in the following analysis process.

Table 3.5.3 The information of subjects and summarized questionnaire results (classification rules are in Table 2.2.1, the details of the sub-scales of attitude to WT are in Table 3.5.2).

Subject	**Hand**	**Gender**	**HP**	**GNS**	**GHQ**	**PA**	**NA**	**Attitude to WT**						
								AT1	A	B	C	D	E	**AT**
P1	R	M	G1	G1	G2	28	45	2	1	2	1	2	1	G1
P2	R	M	G2	G2	G1	27	17	1	1	5	3	1	3	G2
P3	R	M	G2	G3	G1	39	21	1	1	3	1	5	1	G2
P4	R	F	G2	G2	G2	40	17	4	2	3	2	3	3	G2
P5	R	M	G1	G1	G1	32	19	1	1	3	1	1	1	G1
P6	R	F	G1	G3	G2	39	21	1	2	1	1	2	2	G1
P7	R	M	G2	G3	G2	39	40	1	1	2	1	1	1	G1
P8	R	M	G1	G2	G1	26	25	2	2	3	2	3	3	G2
P9	R	F	G2	G2	G2	32	13	2	1	3	1	3	2	G2
P11	R	F	G2	G3	G1	40	34	3	2	4	2	3	3	G2
P12	R	F	G1	G3	G2	37	10	1	2	2	2	3	2	G2
P13	R	F	G2	G2	G2	26	12	3	3	3	2	3	3	G2
P14	R	F	G2	G2	G2	36	14	2	2	5	1	5	2	G2
P16	R	M	G1	G3	G2	27	21	3	1	3	1	4	1	G2

Most of the subjects gave positive or neutral overall opinion to WT. The negative attitude to WT appeared mainly at question B and D that a part of the subjects thought WTs were ugly or unnatural. The subjects were classified into two different groups with the average result of the five specific questions. AT-G1 was the subjects with a more positive attitude to WT (score lower than 2) and AT-G2 with a neutral attitude to WT (the result higher than 2).

The modified SAV (range from 1 to 5) results were collected for all subjects and for different signal groups (Figure 3.5.2). The mean value (black dots) and Standard Deviation (SD) value were calculated. The different SAV results meant that the same WTN combined with different WT visual contents could cause the subjects different annoyance reactions. The SAV of B2 contained only auditory stimulus and was lower than the value of all eight signals, which indicated that the employed visual stimuli could increase the subjects' annoyance, and supported the previous conclusion that people would feel more annoyed when they could not only hear WTN but also see WT. It was found that the SAV of B2 was higher than that of B3, which indicated that the pure auditory signal - WTN could cause stronger annoyance than the pure visual signal - WT. In other words, it was supposed that the annoyance caused by the other combined signals could be considered as mainly from WTN and the corresponding EEG results could be classified as the brain reactions caused by signals with LFN as the predominant component.

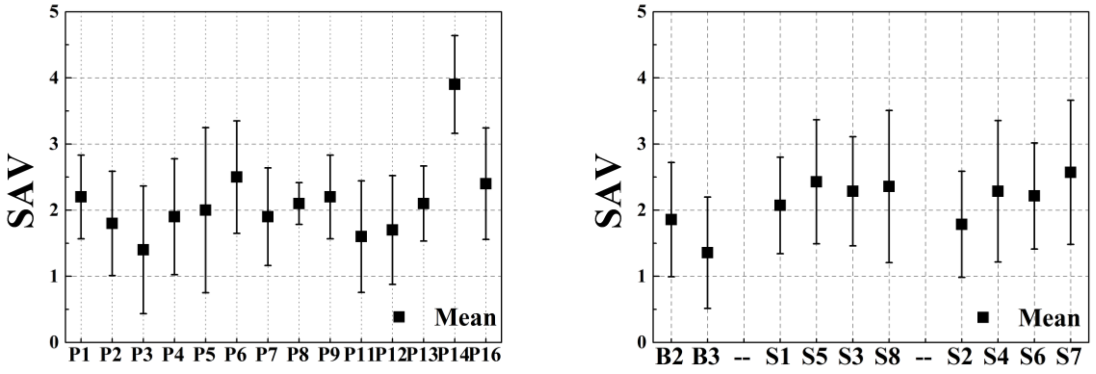


Figure 3.5.2 The SAV (range from 1 to 5) results (mean and SD value) for each subjects (left) and for baseline signals and two signal groups (right)

Figure 3.5.3 is the SAV comparison of two signal groups between different questionnaire groups. The SAV of SG1 showed the annoyance variation between B2 and B3, also among different WT blade rotating speeds. It showed an increasing trend that depended on the speed for most subjects when the blade rotating speed was higher, the SAV was larger, but the growth was not significant. In the comparison between B3 and S5, which contained the same visual stimulus, the SAV of both visual contents of WT and WTN was higher than the SAV of only visual stimulus involved. This result also supported the theory that the combination of visual and auditory contents of WT would enhance the overall negative feeling towards the situation with only one sensory stimulus. Noticeably, the SAV of the low blade rotating speed was largest for GNS-G1 and GHQ-G1, and the SAV of S8 contained with WT in idle state was the lowest for GNS-G1 and highest for AT-G2 in SG1. According to the feedback after the experiment, some subjects said that they didn't notice the different blade rotating speeds, which could be the reason for the small SAV variation among SG1. The SAV of GHQ-G2, AT-G2 and female subjects were found higher than the other corresponding group.

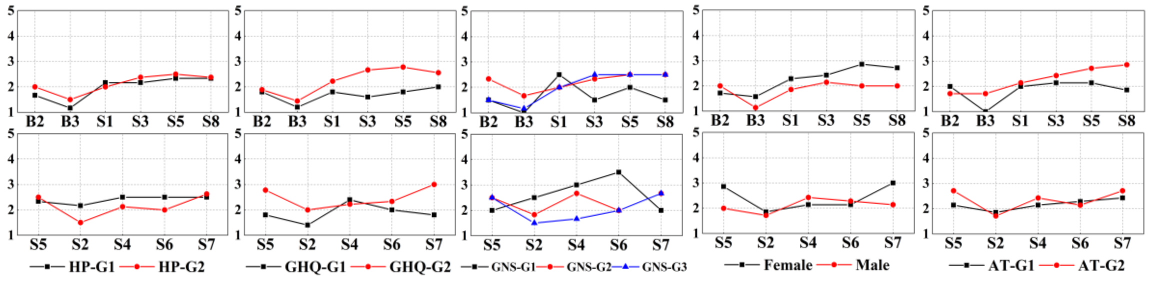


Figure 3.5.3 The comparison of SAV results between groups

(X axis - the upper graph: baseline signals and SG1, the under graph: signal with normal rotating speed (S5) and SG2; Y axis - the SAV result (range from 1-5))

The SAV of S2, S4, and S6 were found lower than that of S5 for subjects of HP-G2, GNS-G2, GNS-G3, GHQ-G2 and for female subjects. The SAV of SG2 for AT-2 who had a neutral attitude to WT was lower than S5. However, the SAV of SG2 was higher than the value of S5 for subjects who had high sensitivity to general noise (GNS-G1). This trend indicated that subjects who had a normal hearing capability, or had normal or low GNS, or normal mental performance, their annoying feelings could decrease when WT was partly unseen, or not directly faced to them, or surrounded with other more natural landscapes. This annoyance reducing effect was especially found for subjects with neutral attitude to WT, and it showed better influence for female subjects than for male subjects. However, subjects who were more sensitive to general noise might feel more annoyed due to these additional landscapes. The SAV of S7, which had several WTs in the video, had the highest annoyance level for most of the subjects. It showed that when there were several WTs in the visual field, subjects could feel more annoyed even when they were exposed to the same WTN.

Because of the visual stimuli in the signal, there were more eye blinks and movement artifacts in the EEG data. After the rejection of all artifacts, the PSD of 10 EEG bands were obtained from the clean EEG data. The relative PSD (RPSD) was calculated as the index which was the ratio of PSD and the baseline PSD (B1) due to the same reason as explained before. Figure 3.5.4 illustrates the summarized RPSD results for each subject, and Figure 3.5.5 depicts for B2, B3 and 8 signals.

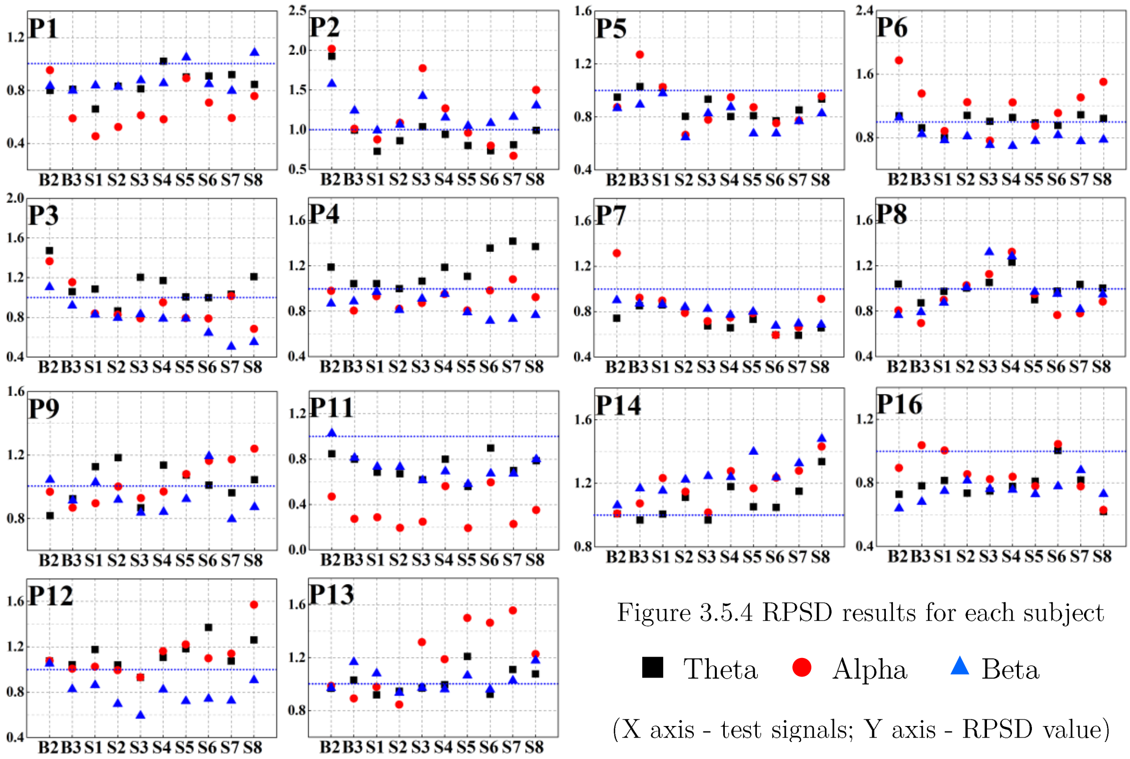


Figure 3.5.4 RPSD results for each subject

■ Theta ● Alpha ▲ Beta

(X axis - test signals; Y axis - RPSD value)

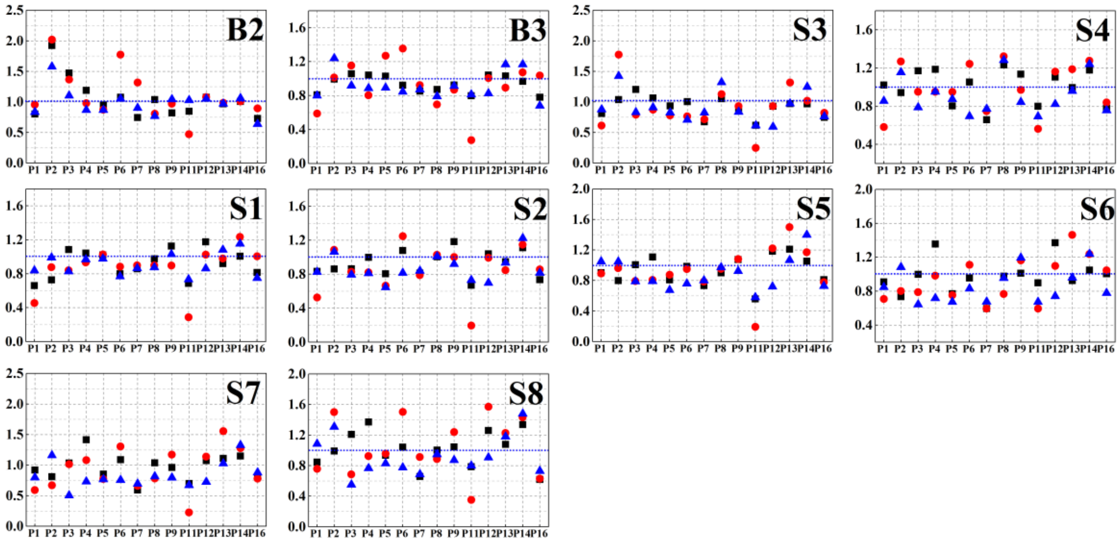


Figure 3.5.5 RPSD results for each signal (baseline2, 3 and Signal 1 - 8)

(figure legends are the same as in Figure 3.5.4; X axis - 14 subjects; Y axis - RPSD value)

The EEG results indicated that brain reaction to the same stimulus was individual. The correlation between SAV and RPSD at four brain function areas was calculated for every subject, and the statistical results were compliant with the results from the other EEG experiments that RPSD of β band had a significant negative relation with SAV at the frontal and temporal area. RPSD of θ band showed a positive correlation with SAV at the occipital area, and the relationship between RPSD of α band and SAV was also insistent but the positive result was found to be dominant at the frontal area, a negative correlation was found at the occipital area.

The RPSD among groups were compared at each electrode position with ANOVA in SPSS (Table 3.5.4). The results showed that there were different brain reactions between subjects with different personality traits. The overall RPSD results were then compared between groups for different signal groups (Figure 3.5.6). The comparison between B2 and B3 was all the same for different groups except for GNS-G1. The varied trend of β band between HP groups was similar, but the amplitude of HP-G2 was higher than the amplitude of HP-G1. The results for two signal groups were not the same for the other questionnaire groups. For SG1 most of the RPSD of three bands for GNS-G2 were higher than that for GNS-G1 and GNS-G3, and the changing trend of β band for GNS-G2 was in opposite with the others. RPSD of α band results between two GHQ groups were also contrary to each other. For SG2 there was a slight difference between HP groups, but the difference between GHQ groups was obvious - the variation for GHQ-G2 was small and for GHQ-G1 was large. The result for RPSD of α band between GNS groups showed almost the same changing trend with a different amplitude, the θ band varied similar between GNS-G1 and GNS-G2 but quite different with GNG-G3, and a similar variation was also found for the β band result between GNS-G2 and GNS-G3. The results of θ, α and β band were all different between female and male subjects.

Table 3.5.4 The ANOVA results of the average RPSD value of the whole scalp and at each electrode position between groups (* means significant).

Theta	HP	GHQ	GNS-G1 : GNS-G2	GNS-G1 : GNS-G3	GNS-G2 : GNS-G3	Gender
AF3	*	*		*	*	
AF4	*					*
O1	*	*	*	*	*	*
O2	*		*	*	*	*
T3	*	*	*	*	*	*
T4	*		*	*	*	*
Average	*		*		*	*
Alpha	HP	GHQ	GNS-G1 : GNS-G2	GNS-G1 : GNS-G3	GNS-G2 : GNS-G3	Gender
AF3	*	*		*	*	
AF4	*	*		*		
O1	*		*	*	*	*
O2	*		*		*	*
T3	*	*	*	*	*	*
T4	*	*	*			*
Average	*		*	*	*	*
Beta	HP	GHQ	GNS-G1 : GNS-G2	GNS-G1 : GNS-G3	GNS-G2 : GNS-G3	Gender
AF3	*	*				*
AF4			*		*	*
O1	*	*			*	*
O2	*	*	*	*	*	
T3	*	*		*	*	
T4	*		*	*	*	*
Average	*		*	*	*	*

To investigate the relation between subjective perception and objective brain reaction caused by the complex stimuli, the correlations between SAV and RPSD of EEG bands were calculated and the significant results summarized (Table 3.5.5). The negative relation for SAV with RPSD of β band and positive relation with θ band at the temporal area were found for all subjects and consent with the early conclusions. The overall RPSD of α band showed positive correlation with SAV at the frontal area. It was noticeable that a positive correlation between RPSD of θ band and SAV at the frontal area was found here.

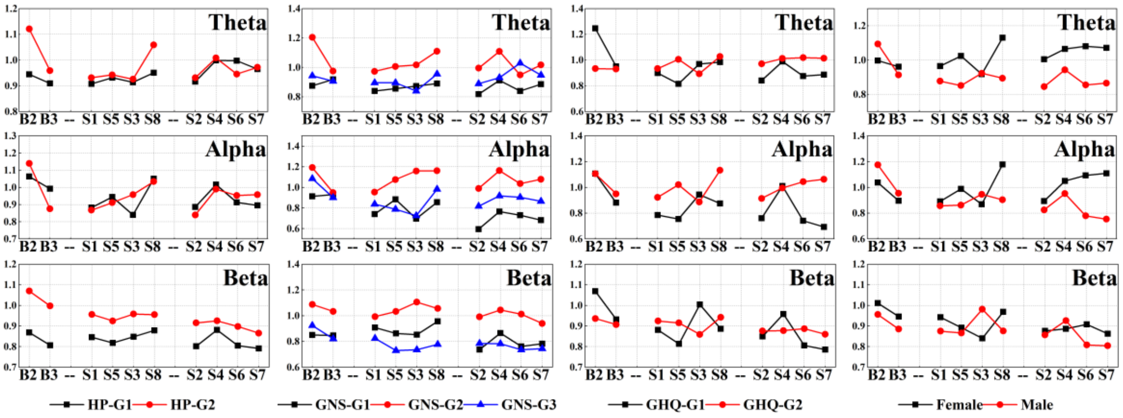


Figure 3.5.6 The comparison of RPSD between groups

(X axis - B2,B3, SG1 and SG2; Y axis - RPSD value)

Table 3.5.5 The significant correlation results between SAV and RPSD of EEG bands for all subjects (using average results) and for questionnaire groups ("+" means significant positive correlation, and "-" means significant negative correlation).

		θ	θ1	θ2	α	α1	α2	β	β1	β2	β3
All	AF3				+						
	AF4		+			+					
	T3		+					-		-	
HP-G1	AF3		+								
	O2	+									-
	T3		+		+						
HP-G2	AF3	+	+		+	+					
	T3							-	-	-	-
GNS-G1	AF4			-	-	-		-		-	-
	O2	+				+					
	T3									-	
GNS-G2	AF3	+								-	
GNS-G3	O1										-
	T3										-
GHQ-G1	T4	+									
GHQ-G2	AF4		+								
	O1			-							
	T3							-			
Male	O1		-								

When analyzing the relations between RPSD and SAV for different questionnaire groups, besides the same result obtained above, there were also some new findings. For example, RPSD of θ band at O2 showed a positive correlation with SAV for HP-G1, and also found for GNG-G1. The significant negative correlation between SAV and RPSD of β band at the frontal area was only found for GNG-G1. Differently, the correlation result was negative for RPSD of θ2 band with SAV at O1, and this result was also found for male subjects just between RPSD of θ1 band and SAV. The eye blink number in each stage was also counted, but there was no significant correlation found for this parameter with SAV or with RPSD of EEG bands.

The SD value of 10 EEG bands for each subject was also compared with SAV. The result showed that the SD of RPSD for β1 band has a significant negative correlation with SAV. So it was assumed that a subject who got larger RPSD variation for β1 band got lower average SAV for all signals. As mentioned above, the subject 10 gave the same and very low SAV to all signals, and his SD result for β1 band was also the highest among all subjects, which was agreed with the obtained relationship result.

The results obtained from the subjective evaluation test and EEG observation using the same WTN combined with different visual signals of WTs as stimuli could be summarized as follows:

- Adding visual information to auditory signal could enhance the overall subjective sensation. And for the situation of adding visual content about WT to WTN the overall annoying feelings could increase. But the annoyance caused by WTN combined with WT and some other landscapes together, or WTN with WT from the 90° side or partly covered by trees was found smaller than the SAV of WTN combined with WT directly facing to the subjects. And this effect was found particularly for subjects with normal hearing ability, or with normal or low general noise sensitivity, or who had a neutral attitude to WT. This annoyance reducing effect worked also better for female than male subjects. Noticeably, the extra landscape or adjustment of the WT could cause stronger annoyance for subjects with high GNS.
- The significant correlation between SAV and RPSD was found at the temporal lobe for β band, which was agreed with the previous finding that β band power had relation with emotional phenomena caused by stimuli related with LFN. Also the positive relation between SAV and RPSD of θ band at the temporal area, as well as between SAV and RPSD of α band at the frontal area, were the same conclusions as obtained when there were only auditory stimuli involved. And RPSD of θ band showed a positive relation with SAV at the frontal area, which also appeared in experiment 3.4.
- Some new results were found for subjects with different personality traits. For subjects with high GNS the positive correlation between SAV and RPSD of θ band at O2 was found, and also the negative relation for SAV with RPSD of α band at the frontal area. A positive relation at the occipital area was supposed due to the additional visual stimuli.

> The negative relations between SAV with RPSD of θ band at O1 for subjects with well mental performance and male subjects were also different findings compared with the early results.

The annoyance caused by WTN was higher than that of WT, so WTN could be considered as the dominate source for annoyance in the combination signals. Therefore, the brain reaction to such stimulus was supposed to have a similar relation with the subjective evaluation result when there was only LFN involved. The correlation results between SAV and RPSD of different EEG bands were proven the hypothesis. When the brain dealt with such combined signals, the power changings at different brain function areas had similar relations with the annoying feelings reported by subjects to the situation when there was only LFN related signal. Another important finding was the annoyance reduction effect due to the natural landscape or suitable adjustments for WT, which could be used to help improve the life situation for people living around WTs. The synchronization between the auditory and visual stimulus was not considered here, which was important for WT and WTN in reality. But the used visual stimuli were field recordings, and the WTN was designed as the noise from WT in general situation which could be masked by other kinds of noise and without obvious variation in the time domain, therefore the combination of WT and WTN in this test could simulate the real situation to a certain extent.

4 The relation between the perception of LFN and psychoacoustic parameters

Generally, when a person hears a sound which travels through the air, firstly the sound arrives at the ear as a mechanical sound. Then inside the ear the sound is transformed into neural action potentials, which will go to the brain to be perceived by the person. At last, this person will have a perception and reaction caused by the sound with the characteristic of the sound itself and also with his/her personality traits. Therefore, theoretically it is possible to separate the hearing process into different stages, and simulate their functions then predict the final reactions. For example, in the experiment 3.4 when the levels of the test signals were the same and the hearing ability of the subjects were similar, thus theoretically the perception and reaction caused by the LFN related signals could be explained and predicted by the character of the signals and modified with personality traits. The character of signals could be calculated with psychoacoustic parameters, and the personality traits which could be measured by different questionnaires related with noise sensitivity, mental performance, stress situation, etc. This was also the hypothesis of using software and subjective questionnaires to predict and quantify the effect caused by LFN.

One aim of this chapter is to verify this hypothesis and find out the proportions of psychoacoustic parameters and personality traits for the perception and reaction on LFN, which is mainly the annoyance and loudness caused by LFN. The other aim is to observe whether there are different prediction models between LFN sufferers and reference subjects. Therefore, the first part of this chapter was the principles and modelling methods of the psychoacoustic parameters which were presumed having relations with the subjective feelings caused by LFN related signals, and then to simplify and narrow down the range of the parameters for the calculation in the next steps. The second part was the correlation analysis for the evaluated annoyance and loudness with the selected psychoacoustic parameters, which was to get more concrete relations. The last part was the quantitative calculation, which was to find out the proportion of using psychoacoustic parameters to predict the annoyance and loudness caused by LFN combined with different components, and the function of the used questionnaires in the model processing. Therefore, the calculation and comparison were made for LFN sufferers and reference subjects separately and also compared between groups which were classified by different questionnaires.

4.1 The selected psychoacoustic parameters

Considering the results of other studies, the following psychoacoustic parameters were firstly selected and calculated with ArtemiS Suit 7.0. Table 4.1.1 shows the information of the primary psychoacoustic parameters and the setting for the software.

Table 4.1.1 The information of the pre-selected psychoacoustic parameters in ArtemiS Suit 7.0 (the parameters in blue are the ones used in the following calculations).

Psychoacoustic parameters	**calculated value**	**unit**	**abb.**	**Function**	
Degree Of Modulation (AM) vs. Time	**average (without 0)**	%	**MD-A**	Band Type	Standard Band
				Bands	Octave
				Band Number	5
				Envelope Lowpass	200 Hz
Modulation Frequency vs. Time	average (10-100Hz)	Hz - s	MF-A	Spectrum Size	256
				Window Function	Hanning
Modulation Spectrum	curve	Hz - dB	-	Overlap [%]	50
Loudness vs. Time	**single value***	soneGF	**L**	Loudness Method	DIN 45631/A1
	average	soneGF	L-A	Sound field	Free
				Scale	Sone
Fluctuation Strength vs. Time	single value	vacil	FS	Resolution	1/1 Bark
	max	vacil	**FS-M**		
	max time	s	FS-T		
Specific Fluctuation Strength	single value	vacil	SFS	Resolution	1/1 Bark
	max	vacil	**SFS-M**		
	max frequency	Bark	SFS-F		
Roughness (Hearing Model) vs. Time	single value	asper	R	Resolution	1/1 Bark
	max	asper	**R-M**		
	max time	s	R-T		
Sharpness vs. Time	**single value**	acum	**S**	Sharpness Method	Aures
	average	acum	S-A	Loudness Method	DIN 45631/A1
				Sound field	Free
Impulsiveness (Hearing Model) vs. Time	**single value**	iu	**Imp**	Abscissa range	Default
	max	iu	**Imp-M**	Quantity	Sound Pressure
	max time	s	Imp-T	Unit	dB (SPL)
Specific Impulsiveness (Hearing Model)	single value	iu	SImp	Resolution	1/1 Bark
Tonality DIN45681	single value	dB	T	Spectrum Size	8192
				Band Type	Standard Band
Psychoacoustic Annoyance			**PA**		

* Loudness - single value is N5 (the 5% percentile value of the time-dependent loudness curve)

The used hearing model, which was based on the physiology of the human hearing and allowed special analysis functions in the frequency domain, were a time and frequency resolution and corresponding to those of human hearing. The following paragraphs were the introductions of the principle and modelling method of the primary selected psychoacoustic parameters.

- **Loudness**

Loudness is the sensation value of the human perception of sound volume, and a dominant feature for any sound quality evaluation. The unit of loudness is sone. A sine tone of the frequency 1 kHz with a level of 40 dB has by definition a loudness of 1 sone. The used method DIN 45631 standardizes a graphic procedure according to Zwicker (Fastl and Zwicker, 2007), which is with a computer program and instruction for the correction of low frequency components according to the curves of equal loudness. Figure 4.1.1 shows the calculation instruction for the time-dependent loudness according to DIN 45631/A1 (HEAD Acoustics, 2013). The individual components were explained as follows:

A) Using a filter bank contained with 28 Chebyshev filters (6th order) to calculate the third-octave levels in time.
B) Establishment of the third-octave bands by squaring of time-dependent parameters of intensity.
C) Smoothed temporal succession through low pass filters.
D) Calculations of the main loudnesses according to the DIN norm standard, in which the signals of low pass filters are processed differently.
E) Using the diode network described by Zwicker to generate a fade-out time dependent on duration.
F) Taking 20 main loudnesses to sum the loudness.
G) Using two low pass filters of the 1st order (time constant 3.5 and 70 ms) to summarize and add together for the total loudness.

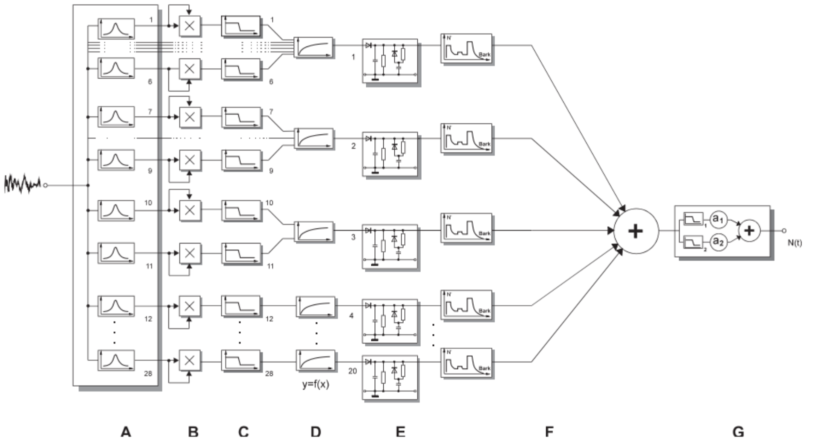


Figure 4.1.1 Calculation of time-dependent loudness according to DIN 45631/A1(HEAD Acoustics, 2013)

- **Roughness**

Roughness and fluctuation strength describe the modulation of the signal, which is the human perception of temporal variations of sounds. With increasing roughness, noise emissions could be perceived as noticeable and also as increasingly aggressive and annoying. Roughness depends on the center frequency, the modulation frequency, but is only slightly influenced by the signal level variation. The unit of roughness is asper. A sine tone of 1 kHz with a level of 60 dB, amplitude-modulated at a frequency of 70 Hz and with a modulation depth of 1, is defined to have a roughness of 1 asper. The sensation of roughness occurs during the existence of time varying envelop over a critical band, when a tone varies in the amplitude or frequency. When the frequency modulation is between 20-300 Hz, sound is perceived as rough. The chosen analysis Roughness (Hearing Model) vs. Time function is a simulation of the signal processing of the human hearing and judges the roughness of a signal in a similar way as the human hearing system (HEAD Acoustics, 2014).

The block diagram shown in Figure 4.1.2 illustrates the roughness calculation based on the hearing model (R. Sottek, 1994). Firstly, the influence of outer and middle ear is considered filtering the audio signal. Then the signal is subdivided by a filter bank with parallel and overlapping band-pass filters, and using the Hilbert transformation to determine the envelopes of the partial band signals. The step to take the threshold in quiet into account means that the excitation levels are reduced (approx. 20 dB/decade for frequencies below 500 Hz). The following 3rd order low-pass filter has a cutoff frequency about 120 Hz at 1 kHz, which is due to the fact that the human ear cannot track the variation of the envelope above a certain rate. Afterwards, the envelope variations are distorted in a nonlinear way. The next step is to calculate the autocorrelation function (ACF). Then the partial roughnesses are obtained with 3rd order high-pass filters (the cutoff frequency - approx. 120 Hz at 1 kHz) and an amplification $\mathrm{g_R}\left(\mathrm{z_i}\right)$ due to a kind of masking effect. At last, the total roughness is calculated by integrating the partial roughnesses.

- **Fluctuation strength**

A difference between roughness and fluctuation strength is that a rough sound is perceived at a constant level whilst a fluctuating sound is perceived to have variations in amplitude. The fluctuation strength is caused by signal variations with very low modulation frequencies, and the calculation in the ArtemiS is done similarly to the calculation of roughness. The unit vacil is defined by the same sine tone as in the case of roughness, except that the modulation frequency is 4 Hz instead of 70 Hz. The modelling equation (4.1) can be described as following:

$$F = \frac{0.008\int_0^{24\mathrm{Bark}} \left(\Delta L/\mathrm{dB\ Bark}\right) dz}{\left(f_{\mathrm{mod}}/4\mathrm{Hz}\right) + \left(4\mathrm{Hz}/f_{\mathrm{mod}}\right)} \mathrm{vacil} \tag{4.1}$$

In which, f_{mod} is the modulation frequency and ΔL is the masking depth.

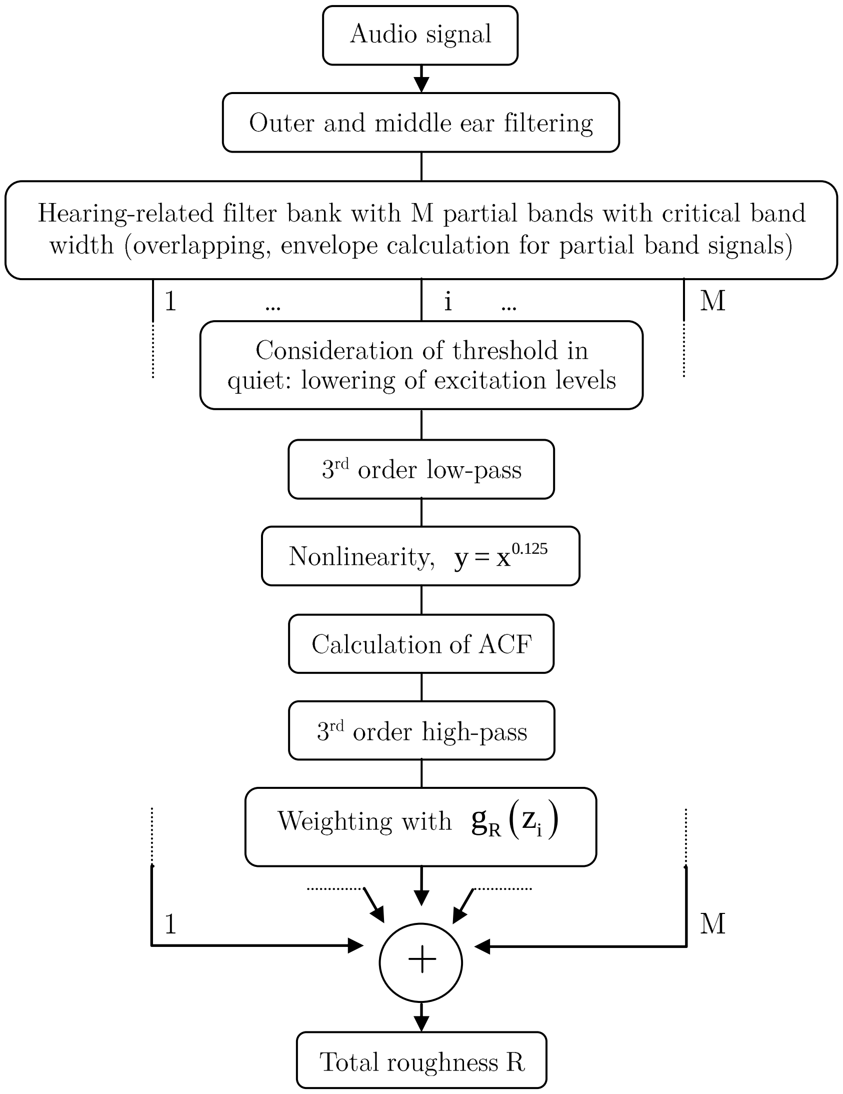


Figure 4.1.2 Block diagram of the roughness calculation based on the hearing model according to Sottek (R. Sottek, 1994)

▪ Sharpness

Sharpness is a sensation value which is caused by high frequency components in a given noise, and its calculation is based upon the specific loudness distribution of the sound. The unit is acum, which is the sharpness produced by a narrow-band noise with critical-band width at a center frequency of 1 kHz having a level of 60 dB. The overall spectral envelope is the main factor influencing sharpness, and the bandwidth within a critical band has almost no influence on sharpness. Considering that sharpness increases with critical-band rate for center frequencies below 3 kHz approximately (16 Bark) and increases strongly for higher critical-band rates, an equation (4.2) of the following form can be given (Fastl and Zwicker, 2007):

$$S = 0.11 \frac{\int_0^{24 Bark} N' g(z) z dz}{\int_0^{24 Bark} N' dz} acum \tag{4.2}$$

In the equation, N' is the special loudness, and $g(z) = 0.066e^{0.171z}$ is the critical-band-rate dependent factor.

- **Tonality**

The analysis of Tonality DIN 45681 is used to determine the tonal components of noise exposure according to the DIN, which is according to the level differences between tone and background noise in the surrounding frequency group. The German standard computes a “tone adjustment” coefficient used for noise assessment problems. Prominence ratio is the parameter, which is used to assess whether the contained pure tones in the noise with not very high level are prominent or not. Prominence is the ratio between $X_{CB(i)}$ and $\frac{1}{2}\left(X_{CB(i-1)} + X_{CB(i+1)}\right)$, in which $X_{CB(i-1)}$, $X_{CB(i)}$ and $X_{CB(i+1)}$ are respectively the sound pressure of the lower, middle and upper critical band of the critical band containing the tone $X_{CB(i)}$.

- **Impulsiveness**

The impulsiveness of a sound refers to the degree of impulsive content perceived in the sound. Head Acoustics does not give a precise description of the matrix for impulsiveness publicly, but the method is based on the roughness calculation.

- **Psychoacoustic annoyance**

The last parameter is psychoacoustic annoyance (PA), which depends on the loudness, the tone color and the temporal structure of sounds (Fastl and Zwicker, 2007). The formula of PA based on the loudness *N*, sharpness *S*, fluctuation strength *F* and roughness *R* is as given:

$$PA = N_5 \left(1 + \sqrt{w_S^2 + w_{FR}^2}\right) \tag{4.3}$$

with N_5- percentile loudness in sone

$$w_S = \left(\frac{S}{\text{acum}} - 1.75\right) \cdot 0.25 \lg\left(\frac{N_5}{\text{sone}} + 10\right) \quad \text{for } S > 1.75 \text{ acum}$$

$$w_{FR} = \frac{2.18}{\left(N_5/\text{sone}\right)^{0.4}} \left(0.4 \cdot \frac{F}{\text{vacil}} + 0.6 \cdot \frac{R}{\text{asper}}\right)$$

The next step was to simplify and narrow down the amount of the primary selected psychoacoustic parameters. The data of LFN1 combined with PN in the experiment 3.1 were used to achieve the goal.

Firstly, the pre-selected psychoacoustic parameters were calculated and then rejected by the rules when the parameter had no difference among all signals, or statistical significance or realistic meaning. The single value of Fluctuation Strength vs. Time and single value of Specific Fluctuation Strength were the same for all signals, so they both were rejected. Due to the same reason the single value of Roughness (Hearing Model) vs. Time was also rejected. The Modulation Frequency vs. time was removed, because the results showed large oscillation in the considered frequency range (< 200 Hz), which meant that there was no significant stable and comparable modulation frequency among signals. The appearing time for the maximum value of Roughness (Hearing Model) vs. Time was different, but the differences were too small to be detected, thus this parameter had no realistic meaning. For the same reason, the appearing time of the maximum value of Impulsiveness (Hearing Model) vs. Time was also rejected. The Prominence Ratio obtained from tonality calculation was unchanged when the original LFN was combined with different PNs. But in experiment 3.4 there was a listening test which was designed by adding PTs with the original LFN to obtain the low frequency sensitivity for each subject and also to investigate the effect of tonal components on annoyance perception. So the Prominence Ratio was also calculated with the data of this test. The obtained result showed that only LFN combined with 100 Hz had a significant, corresponding single Prominence Ratio value, and the other PTs could not be detected, which could be due to the acoustic environment of the used semi-anechoic chamber.

Therefore, the second-selected psychoacoustic parameters were the following. The average value of Degree of Modulation (without zero value) and the average value (10 - 100 Hz) of Modulation Spectrum were used to represent the modulation character. The both parameters for loudness were chosen: the single value of Loudness vs. Time which was actually the N5 value (the 5% percentile value of the time-dependent loudness curve) due to the chosen method. To reduce the effects of the beginning and ending of the auditory stimulus, the first 0.1 s and last 0.1 s were used as fading in and fading out functions, thus the average loudness value was calculated with the data from 0.1 s to 4.9 s. The single value and average value of Sharpness vs. Time were chosen, and the average value was calculated in the same way as for the average loudness. Due to the obvious variations of the maximum value of Roughness (Hearing Model) vs. Time, Fluctuation Strength vs. Time and Specific Fluctuation Strength, and also the results of Impulsiveness (Hearing Model) vs. Time and Specific Impulsiveness (Hearing Model), these parameters were chosen for the next analysis, too.

It was assumed that there were still redundant or overlapped parameters, so the second-selected psychoacoustic parameters - PA, MD-A, MF-A, L, L-A, S, S-A, R-M, FS-M, SFS-M, Imp, Imp-M and SImp were calculated and compared to simplify for the further analysis. Table 4.1.2 shows the significant correlation results between parameters without PA.

The results for parameters belonging to the same character of the signal were compared, which were in the overstriking blocks. MD-A and MF-A got high positive correlation results. L had a high positive relation result with L-A, so it was between S and S-A. The correlation between the maximum value obtained from Fluctuation Strength vs. Time (FS-M) and the maximum value of Specific Fluctuation Strength (SFS-M) was not significant. SImp showed high positive correlation with Imp and a high negative correlation with Imp-M, and the relationship between Imp and Imp-M was negative.

Table 4.1.2 Cross correlation results between second-selected psychoacoustic parameters (the red results in the block are the compared parameters).

	MD-A	MF-A	L	L-A	S	S-A	R-M	FS-M	SFS-M	Imp	Imp-M	SImp
MD-A		**.895**					.719					
MF-A					-.702	-.702	.798			.781	-.819	.825
L				**.997**	.911	.911	-.937					
L-A					.895	.893	-.923					
S						**.999**	-.947					
S-A							-.945					
R-M												
FS-M										.810	-.778	.828
SFS-M										.747		
Imp											**-.849**	**.978**
Imp-M												**-.938**
SImp												

After that the Cluster Analysis and NMDS were made to identify the similarity among the second-selected parameters in SPSS with Z scores. That was made because of the different scales of the psychoacoustic parameters. Hierarchical Cluster Analysis was chosen, and Between-groups linkage and Square Euclidian Distance were the cluster and measure methods. The classification result (Figure 4.1.3) indicated that S and S-A, L and L-A, MD-A and MF-A, Imp and SImp were near to each other separately and were classified in the first step, which was consistent with the correlation result. It supposed that the parameters with high correlation results in theory had the similar contribution or function to represent the corresponding character of the test signals. The Stress of NMDS was .03483, and RSQ was 0.99420, which meant a “Good” result. In Figure 4.1.4, the positions of S and S-A, L and L-A, Imp and SImp also confirm the correlation and classification results.

Therefore, considering the statistical calculation results and the complexity of the calculation procedures of each parameter, the final selected psychoacoustic parameters for the further investigation were the psychoacoustic annoyance (PA), the average value of the Degree of Modulation (MD-A; without zero value), the single value of Loudness vs. Time (L), the single value of Sharpness vs. Time (S), the maximum value of Fluctuation Strength vs. Time (FS-M), the maximum value of Specific Fluctuation Strength (SFS-M), the maximum value of Roughness (Hearing Model) vs. Time (R-M), the single value (Imp) and the maximum value from Impulsiveness (Hearing Model) vs. Time (Imp-M). These parameters are emphatically pointed out in Table 4.1.1.

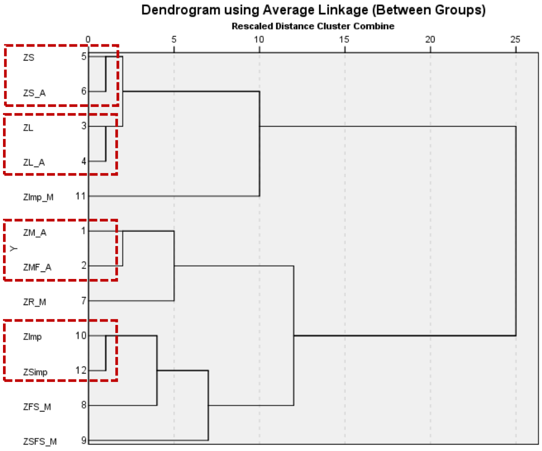


Figure 4.1.3 The classification result

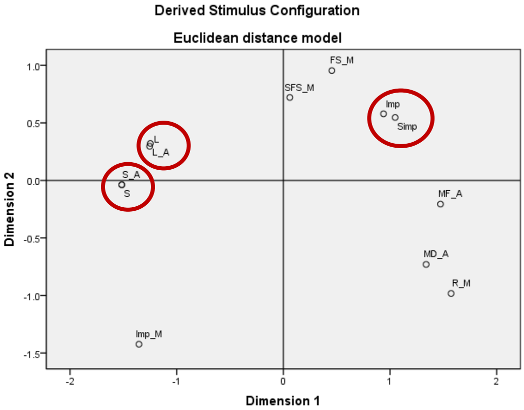


Figure 4.1.4 The NMDS result

4.2 The correlation of psychoacoustic parameter with SAV and the evaluated loudness

Then the final selected psychoacoustic parameters were calculated for the stimuli in experiment 3.1 (LFN1+PN, LFN4+PN), 3.3 and 3.4 with ArtemiS suit 7.0, and the Spearman's correlation between the obtained data and corresponding SAV results was calculated in SPSS 21. The results of experiment 3.1 showed that there was a significant negative correlation between SAV and MD-A for LFN1 combined with PN in 15 dB. PA, L and SFS-M showed significant negative relationships with SAV for LFN4 combined with PN in 20 dB. Table 4.2.1 is the result for experiment 3.3.

Table 4.2.1 The significant correlation results between SAV and psychoacoustic parameters for experiment 3.3 ("+" means positive correlation, "-"means negative correlation).

	PA	MD-A	L	S	FS-M	SFS- M	R- M	Imp	Imp- M
LFN1+PN	+						-		
LFN4+PN	+			+					

The following results were for experiment 3.4. Table 4.2.2 and Table 4.2.3 are the correlation results for SAV and the evaluated loudness with psychoacoustic parameters for LFN combined with PTs, which were the stimuli in the low frequency sensitivity listening test. The results showed no significant correlation between SAV and PA, and the positive correlation between SAV and L was only found for GHQ-G2. Considering the test signals the impulsive feeling was supposed to change, and it was proven by the negative relationships of Imp and Imp-M with SAV for reference, LFNS-G2, PANAS-G2 and PSS-G2, which were classified as relative "normal" groups. For the same reason, the fluctuation strength was also supposed to increase due to the added PT, and the significant positive correlation between SAV and FS-M or SFS-M was agreed with earlier conclusions that stronger fluctuation could cause increased annoyance. No higher frequency components were added or changed in the test signal, so sharpness and roughness were supposed to change slightly and have little contribution to the annoyance, which was confirmed by the non-significant correlation for S and R-M wit SAV. The significant positive relations between the evaluated loudness and L were found for all subject groups. The positive correlation between the evaluated loudness and PA was also found for most groups except for LFN sufferers and GNS-G1.

Globally, the subjective annoyance caused by LFN combined with PT was a complex feeling and depended on many factors which were reflected from its relations with FS and Imp. The evaluated loudness was a relative "pure" and easier assessed feeling which was highly correlated with PA and L. The hardly obtained relation between SAV and PA indicated that the annoyance caused by LFN with tonal character could not be well predicted by PA, thus the other psychoacoustic parameters, like impulsiveness and fluctuation strength should be considered.

Table 4.2.2 Correlation results between SAV and psychoacoustic parameters for LFN combined with PTs ("+" means significant positive relationship, "-" means significant negative relationship).

SAV	PA	L	S	FS-M	SFS-M	R-M	Imp	Imp-M
All				+	+		-	-
Reference group				+	+		-	-
LFN Sufferers								
GNS-G1				+				
GNS-G2								
LFNS-G1								
LFNS-G2				+	+		-	-
GHQ-G1								
GHQ-G2		+						
PANAS-G1								
PANAS-G2				+	+		-	-
PSS-G1								
PSS-G2				+	+			-
Chinese								
German (without sufferers)				+	+		-	-

Table 4.2.3 Correlation results between the evaluated loudness and psychoacoustic parameters for LFN combined with PTs ("+" means significant positive relationship, "-" means significant negative relationship).

Evaluated loudness	PA	L	S	FS-M	SFS-M	R-M	Imp	Imp-M
All	+	+						
Reference group	+	+						
LFN Sufferers		+						
GNS-G1		+						
GNS-G2	+	+						
LFNS-G1	+	+						
LFNS-G2	+	+		+				
GHQ-G1	+	+						
GHQ-G2	+	+		+				
PANAS-G1	+	+						
PANAS-G2	+	+		+				
PSS-G1	+	+						
PSS-G2	+	+						
Chinese	+	+						
German (without sufferers)	+	+						

Table 4.2.4 and Table 4.2.5 are the correlation results for SAV and the evaluated loudness with psychoacoustic parameters for LFN combined with PNs, which were the stimuli in the indirect method listening test (experiment 3.4). The similar result for the evaluated loudness was obtained: it had significant positive correlation with PA and L for most groups. In addition, S showed a positive relation, FS-M and SFS-M showed negative relations with the evaluated loudness.

SAV caused by LFN combined with PNs was found positively correlated with PA and L except for LFN sufferers, GNS-G1 and LFNS-G1, which was very different with the above results in Table 4.2.2. The reason for the difference could be the added PNs in middle or high frequencies. The high positive correlation results for S with SAV and the evaluated loudness confirmed that the extra sharpness caused by PN could increase the total annoyance and loudness for most subjects except for LFN sufferers and subjects with high GNS or LFNS. The correlations between SAV and FS-M or SFS-M were also significant. The same result was also found for the evaluated loudness, but the correlation trend was in contrast with the result for LFN combined with PT. The possible explanation was that the added PT increased the fluctuation feeling, but

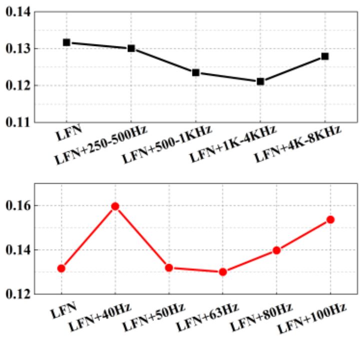


Figure 4.2.1 The FS-M results of LFN combined with PTs (upper) and with PNs (under)

(X axis - test signals; Y - FS-M value (vacil)) the time structure of the original LFN was changed due to the additional PN and the variation of the envelope was decreased because of the masking effect. Figure 4.2.1 is the FS-M results of LFN combined with PTs and with PNs.

Table 4.2.4 Correlation results between SAV and psychoacoustic parameters for LFN combined with PNs ("+" means significant positive relationship, "-" means significant negative relationship).

SAV	PA	L	S	FS-M	SFS-M	R-M	Imp	Imp-M
All	+	+	+	-	-			
Reference group	+	+	+	-	-			
LFN Sufferers								
GNS-G1				-	-			
GNS-G2	+	+	+					
LFNS-G1				-	-			
LFNS-G2	+	+	+	-	-			
GHQ-G1	+	+	+	-	-			
GHQ-G2	+	+	+	-	-			
PANAS-G1	+	+		-	-			
PANAS-G2	+	+	+	-	-			
PSS-G1	+	+	+	-	-			
PSS-G2	+	+	+	-	-			
Chinese	+	+	+	-	-			
German(without sufferers)	+	+	+					

Table 4.2.5 Correlation results between the evaluated loudness and psychoacoustic parameters for LFN combined with PNs ("+" means significant positive relationship, "-" means significant negative relationship).

Evaluated loudness	PA	L	S	FS-M	SFS-M	R-M	Imp	Imp-M
All	+	+	+	-	-			
Reference group	+	+	+	-	-			
LFN Sufferers								
GNS-G1	+	+	+	-	-			
GNS-G2	+	+						
LFNS-G1				-	-			
LFNS-G2	+	+	+					
GHQ-G1	+	+	+	-	-			
GHQ-G2	+	+						
PANAS-G1						+		
PANAS-G2	+	+	+					
PSS-G1								
PSS-G2	+	+	+	-	-			
Chinese	+	+	+	-	-			
German(without sufferers)	+	+	+	-	-			

4.3 The predicting models for annoyance and loudness caused by LFN

The above correlation results between subjective evaluations and psychoacoustic parameters indicted that the evaluated loudness had a well positive relationship with L for most subjects when LFN was combined with PTs in low frequency ranges or bandwidths PNs in middle or high frequency ranges. Therefore, it was supposed to obtain the predicting model for loudness caused by LFN related signals using psychoacoustic parameter L as the variable. The regression calculation was made in SPSS to find out a more precise relation between the evaluated loudness and L. It was also to observe whether there were other psychoacoustic parameters or personality traits that had influence on the loudness perception caused by LFN related signals.

The first regression calculation was the linear regression, the evaluated loudness was the dependent variable and L obtained from ArtemiS was the independent variable. Table 4.3.1 depicts the main results. The "R Square" column represents the coefficient of determination, which is the proportion of variance in the dependent variable that can be explained by the independent variable. Here R square showed the extent of L predicting the evaluated loudness, and the higher R value meant the better regression result. The ANOVA result tests whether the overall regression model is a good fit for the data, and the *p* value (sig.) lower than 0.05 is usually acceptable. As that the regression model and statistically significantly predicts the outcome variable. The unstandardized coefficients results provided the necessary information to predict the evaluated loudness from L, as well as determined whether L contributed statistically and significantly to the model ($p<0.05$).

The ANOVA results showed that L could well predict the evaluated loudness caused by LFN combined with PT or PN, and the high R square value indicated a good level of the regression. For example, the predicted loudness value caused by LFN combined with PT for the reference group could be calculated with the “B” value in Table 4.3.1:

$$Loudness_P = -1.623 + 0.335L$$

, in which L was the psychoacoustic loudness value,

and the predicted loudness of LFN combined with PN for the reference group could be calculated with the equation:

$$Loudness_P = -3.286 + 0.66L \quad .$$

Figure 4.3.1 shows the predicting curves for the significant results. The gradient values of the loudness predicting curves were not exactly the same between groups, but the variation was small.

Table 4.3.1 The linear regression results of the evaluated loudness using L as the variable for experiment 3.4.

		R Square	ANOVA (sig.)	Unstandardized Coefficients			
				B		Sig.	
				(Constant)	**L**	(Constant)	L
LFN + PT	**All**	.812	**.014**	-1.493	.326	.038	.014
	Reference group	.870	**.007**	-1.623	.335	.016	.007
	LFN Sufferers	.371	.200	-.492	.183	.546	.200
	GNS-G1	.389	.186	-.668	.194	.430	.186
	GNS-G2	.868	**.007**	-1.600	.331	.017	.007
	LFNS-G1	.527	.102	-.797	.226	.299	.102
	LFNS-G2	.885	**.005**	-1.505	.314	.013	.005
	GHQ-G1	.579	.079	-.918	.240	.224	.079
	GHQ-G2	.865	**.007**	-1.517	.317	.018	.007
	PANAS-G1	.600	.071	-.982	.242	.187	.071
	PANAS-G2	.845	**.009**	-1.596	.334	.023	.009
	PSS-G1	.744	**.027**	-1.417	.314	.070	.027
	PSS-G2	.821	**.013**	-1.514	.326	.034	.013
	Chinese	.775	**.021**	-1.241	.292	.065	.021
	German (without sufferers)	.933	**.002**	-1.403	.299	.005	.002
LFN + PN	**All**	.996	**.000**	-2.931	.593	.000	.000
	Reference group	.952	**.005**	-3.286	.660	.007	.005
	LFN Sufferers	.007	.897	.297	.043	.877	.897
	GNS-G1	.919	**.010**	-2.483	.514	.016	.010
	GNS-G2	.974	**.002**	-3.196	.639	.003	.002
	LFNS-G1	.703	.076	-2.644	.507	.094	.076
	LFNS-G2	.892	**.016**	-3.020	.618	.024	.016
	GHQ-G1	.967	**.003**	-2.638	.538	.004	.003
	GHQ-G2	.967	**.003**	-3.098	.623	.004	.003
	PANAS-G1	.615	.116	-2.169	.436	.155	.116
	PANAS-G2	.901	**.014**	-2.882	.600	.022	.014
	PSS-G1	.478	.196	-2.098	.414	.241	.196
	PSS-G2	.950	**.005**	-3.033	.623	.008	.005
	Chinese	.926	**.009**	-3.271	.664	.014	.009
	German (without sufferers)	.856	**.024**	-2.934	.594	.036	.024

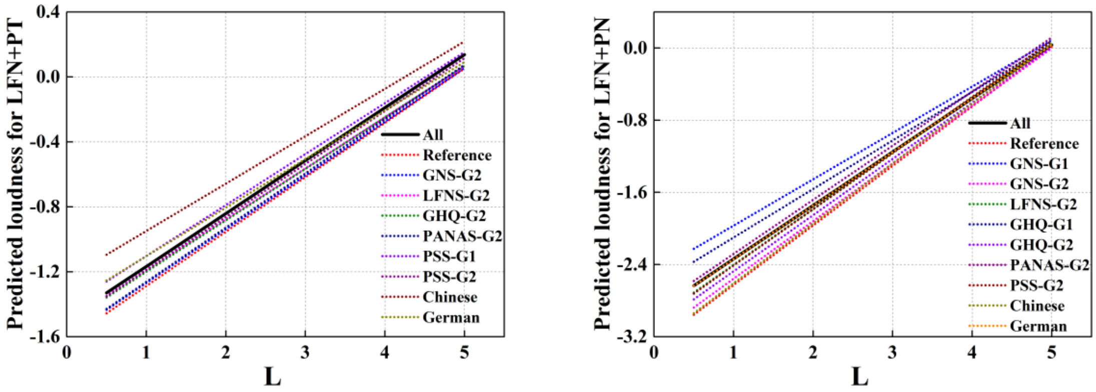


Figure 4.3.1 The predicted loudness for LFN combined with PT (left) and with PN (right)

(X axis - the psychoacoustic loudness value; Y axis - the predicted loudness level for LFN+PT (left), and for LFN+PN (right))

The cases, which got non-significant ANOVA and lower R square value in the linear regression result, were found for LFN sufferers, GNS-G1, LFNS-G1, and PANAS-G1 in the LFN combined with PT test, and for LFN sufferers, LFNS-G1, PANAS-G1 and PSS-G1 in the LFN combined with PN test. For these situations the curve estimation calculation was made to investigate whether there were other predicting forms for the evaluated loudness using L, or with other psychoacoustic parameters (except PA) as the variables. Table 4.3.2 is the summarized result. Except for LFN sufferers in the LFN combined with PN test, the significant results were found with L as the independent variable and in the "Quadratic" equation type for all the above mentioned cases. Figure 4.3.2 is the comparison between the evaluated loudness and the predicted loudness value from L for the reference group and for LFN sufferers in both tests with regression equation.

Table 4.3.2 The curve estimation results of the evaluated loudness using L as the variable for the non-significant results in the linear regression for experiment 3.4.

	Groups	Equation	Model Summary		Parameter Estimates		
			R Square	Sig.	Constant	b1	b2
LFN+PT	LFN sufferers	Quadratic	.898	.032	-9.358	2.975	-.212
	GNS-G1	Quadratic	.983	.002	-10.419	3.265	-.234
	LFNS-G1	Quadratic	.956	.009	-9.055	2.826	-.198
	GHQ-G1	Quadratic	.971	.005	-8.928	2.762	-.192
	PANAS-G1	Quadratic	.945	.013	-8.431	2.588	-.179
LFN+PN	LFNS-G1	Quadratic	.933	.067	17.693	-6.598	.613
	PANAS-G1	Quadratic	.924	.076	19.518	-7.140	.654
	PSS-G1	Quadratic	.978	.022	27.721	-10.002	.899

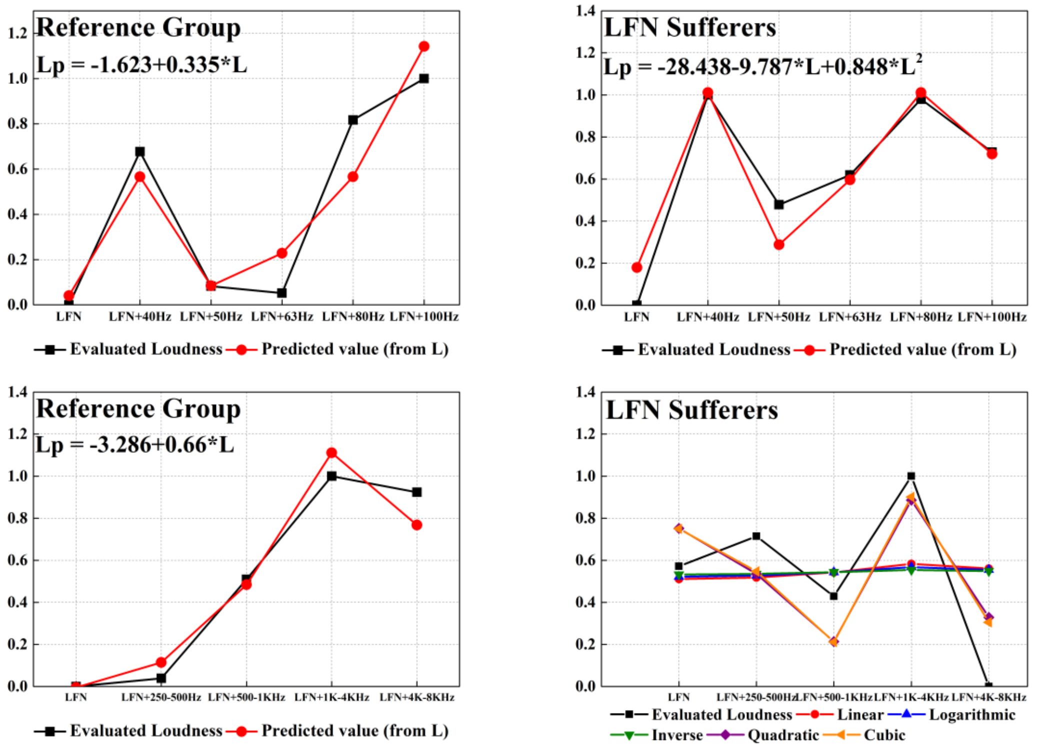


Figure 4.3.2 The comparison between evaluated loudness and predicted loudness value for the reference group and LFN sufferers in experiment 3.4

(X axis - (upper graphs) LFN, LFN+40Hz, LFN+50Hz, LFN+63Hz, LFN+80Hz, LFN+100Hz; (under graphs) LFN, LFN+250-500Hz, LFN+500-1KHz, LFN+1K-4KHz, LFN+4K-8KHz); Y axis - loudness value)

The linear regression and curve estimation results indicated that the loudness perception caused by LFN related signals could be well predicted by the psychoacoustic parameter - Loudness (L). For most situations, the predication relation was linear, and a higher L was obtained from the signal the louder the subject could feel. But for the subjects with higher GNS or stronger stress, the prediction equation was in the “Quadratic” form. The evaluated loudness of LFN combined with PT in the low frequency range had no significant relationship with L or with other single psychoacoustic parameter for LFN sufferers. This unpredictable result could be because of their special perception and reaction on LFN, which could cause them to have stronger influence from LFN than the others. In other words, LFN sufferers could be very sensitive, or have almost equal sensitivity in the low frequency range, and the just detectable tonal effect didn’t change their loudness judgement in the similar trend as the others.

The correlation between annoyance caused by LFN related signals and the psychoacoustic parameters values of these signals was not significant in experiment 3.1 and 3.3, which didn’t match the assumption for the linear regression. So other non-linear curve estimations were used to investigate their relationship. The calculation was made for each selected psychoacoustic parameter as the independent variable. Considering the R square and the ANOVA result the significant regressions were found only in some cases for experiment 3.1. And for experiment 3.3 the results of non-linear regression had a similar R square value as that of the linear regression (Table 4.3.3).

Table 4.3.3 The curve estimation results of SAV for experiment 3.1 and 3.3.

Groups	Psychoacoustic parameter	Equation	Model Summary		Parameter Estimates			
			R^2	Sig.	Constant	b1	b2	b3
Experiment 3.1								
LFN4 + PN-20dB	PA	Linear	.580	.017	12.831	-2.097		
		Quadratic	.580	.017	8.562	0.000	-.258	
	L	Linear	.580	.017	12.714	-2.142		
		Quadratic	.580	.017	8.504	0.000	-.272	
LFN4 +PN-All	S	Quadratic	.285	.018	5.598	-5.176	4.855	
		Cubic	.286	.048	5.191	-2.884	.795	2.25
Experiment 3.3								
LFN1 + PN	PA	Linear	.784	.046	-5.273	1.898		
		Quadratic	.789	.044	-1.497	0.000	.238	
	L	Linear	.784	.046	-5.184	1.933		
		Quadratic	.789	.044	-1.453	0.000	.250	
	S	Linear	.868	.021	1.401	2.363		
		Inverse	.824	.033	3.217	-.327		
	R-M	Linear	.954	.004	11.181	-128.12		
		Quadratic	.957	.004	6.781	0.000	-931.81	
LFN4 + PN	PA	Linear	.865	.022	-7.071	2.388		
		Inverse	.871	.021	12.432	-39.792		
	L	Linear	.865	.022	-6.938	2.439		
		Inverse	.871	.021	12.299	-37.913		
	S	Quadratic	.971	.029	-8.545	48.825	-50.836	
		Cubic	.971	.029	-5.665	27.684	0.000	-39.86

It was proven that the value of L, S or R could change when LFN was combined with bandwidth PN in middle or high frequency range, and considering the equation of PA this parameter could also change due to the added components. When only using one variable to predict the annoyance caused by LFN combined with PN, it was supposed that PA could be a suitable psychoacoustic parameter in this study. In addition, the personality traits should also be considered as an important factor, so the regression should be calculated for different questionnaire groups. Firstly, the linear regression was calculated with SAV as the dependent variable and PA as the independent variable for LFN combined with PN (Table 4.3.4). Then curve estimations were made with SAV as the dependent variable and every single psychoacoustic parameter as the independent variable in SPSS for the non-significant situations from the linear regression results (Table 4.3.5). When more than one regression method got a significant value, the equation which was the easiest and with higher R square value was chosen.

Table 4.3.4 The linear regression results of SAV with PA as the variable for LFN combined with the PN test in experiment 3.4.

	Groups	R Square	ANOVA (sig.)	Unstandardized Coefficients			
				B		Sig.	
				(Constant)	PA	(Constant)	PA
Experiment 3.4 LFN+PN	**Reference**	.829	**.032**	-2.327	.494	.056	.032
	LFN Sufferers	.634	.107	-2.424	.479	.147	.107
	GNS-G1	.607	.120	-1.823	.401	.198	.120
	GNS-G2	.900	**.014**	-2.895	.589	.023	.014
	LFNS-G1	.799	**.041**	-2.534	.518	.065	.041
	LFNS-G2	.916	**.011**	-2.769	.565	.018	.011
	GHQ-G1	.888	**.017**	-2.465	.514	.029	.017
	GHQ-G2	.895	**.015**	-2.605	.540	.026	.015
	PANAS-G1	.780	**.047**	-2.402	.507	.080	.047
	PANAS-G2	.895	**.015**	-2.600	.537	.026	.015
	PSS-G1	.865	**.022**	-2.869	.583	.036	.022
	PSS-G2	.839	**.029**	-2.365	.499	.051	.029
	Chinese	.731	.065	-2.064	.451	.115	.065
	German (without sufferers)	.904	**.013**	-3.265	.638	.019	.013

Table 4.3.5 The curve estimation results of SAV for groups with non-significant results in the linear regression for LFN combined with the PN test in experiment 3.4.

Groups	Psychoacoustic parameter	Equation	Model Summary		Parameter Estimates			
			R^2	Sig.	Constant	b1	b2	b3
LFN sufferers	S	Linear	.948	.005	-0.16	0.81		
	Imp	Quadratic	.981	.019	-0.19	12.82	-34.44	
	Imp-M	Quadratic	.985	.015	-1.31	15.64	-26.33	
GNS-G1	FS-M	Linear	.773	.049	9.65	-71.78		
	SFS-M	Linear	.987	.001	64.54	-3919.62		
Chinese	S	Cubic	.999	.035	-2.37	12.24	-13.15	4.26
	SFS-M	Linear	.972	.002	65.77	-3991.84		
	Imp	Inverse	.806	.039	0.84	-0.03		

The above linear and non-linear regression results indicated that annoyance caused by LFN combined with different bandwidth PNs could be well predicted by PA for most subjects. The non-significant results appeared only for LFN sufferers, GNS-G1 and Chinese subjects. Although for other questionnaire groups the results were statistically significant, there were also differences between them. Especially the R square for LFNS-G1 was smaller than that of LFNS-G2, which meant that PA could predict the annoyance caused by LFN combined with PN better for subjects with normal or low sensitivity to LFN, than for LFN subjects who didn't identify as LFN sufferers but with high sensitivity to LFN.

Then the curve estimation analysis showed that S was more suitable than PA to predict the annoyance changes caused by LFN combined with PN for LFN sufferers, and SFS-M was the appropriate psychoacoustic parameter for subjects with higher GNS. The prediction results also indicated that there could be different perceptions and reactions on LFN between Chinese and German subjects due to the different acoustic structure for living environment, culture, evaluation standard, etc. However the amount of the subjects was too small to make a certain conclusion, which should be investigated in the future.

And considering the correlation results between SAV and psychoacoustic parameters for LFN combined with PTs in the low frequency range, the predicting model calculation mainly used curve estimation with SAV as the dependent variable and every single psychoacoustic parameter as the independent variable. Table 4.3.6 shows the regression results. It was found that PA could be used to predict the annoyance caused by LFN combined with low frequency PTs for some groups in the form of “Inverse” or “Cubic”, but FS-M got better results than PA for most subjects. The varied psychoacoustic parameters, due to the added PT, were different compared to the situation when PN was the additional component, which could be the reason why FS-M was found more suitable than PA to predict the annoyance caused by LFN combined with PT.

No significant result was found for LFN sufferers and LFNS-G1, which meant that there was no suitable single psychoacoustic parameter which could well predict annoyance caused by LFN combined with PTs in low frequency ranges for subjects having LFN problems or having high sensitivity to LFN. The reason could be due to the stronger influence of LFN on them, which could mask or reduce the effect of the tonality. The LFN sufferers who joined the tests had hearing impairment at higher frequency, which was because of their age, whereas the whole reference group had a good hearing ability. This difference could possibly cause the same LFN combined with PT differently in the hearing processing, for example, the spectrum heard by LFN sufferers could be in an “unbalanced” form. As a consequence, LFN sufferers usually have stronger low frequency sensitivity in a larger range than the reference group.

Table 4.3.6 The curve estimation results of SAV for LFN combined with PT in experiment 3.4.

Groups	Psychoacoustic parameter	Equation	Model Summary		Parameter Estimates			
			R^2	Sig.	Constant	b1	b2	b3
All	**FS-M**	Linear	.824	.012	-3.22	25.65		
Reference group	PA	Inverse	.676	.045	2.44	-12.02		
	L	Inverse	.685	.042	2.42	-11.52		
	FS-M	Linear	.806	.015	-3.79	30.31		
GNS-G1	**FS-M**	Linear	.713	.034	-3.18	24.68		
GNS-G2	**FS-M**	Linear	.665	.048	-2.99	24.78		
LFNS-G2	PA	Inverse	.673	.046	2.43	-11.80		
	L	Inverse	.681	.043	2.41	-11.31		
	FS-M	Linear	.800	.016	-3.68	29.75		
	SFS-M	Linear	.688	.041	-3.90	263.85		
	Imp	Linear	.683	.043	1.21	-19.75		
GHQ-G2	PA	Cubic	.883	.040	-5.75	1.32	0.00	-0.01
	L	Cubic	.887	.038	-5.56	1.32	0.00	-0.01
	FS-M	Linear	.770	.022	-3.58	29.15		
PANAS-G1	PA	Cubic	.870	.047	-9.12	2.14	0.00	-0.01
	L	Cubic	.872	.046	-8.87	2.15	0.00	-0.02
PANAS-G2	**FS-M**	Linear	.852	.009	-3.41	27.37		
PSS-G1	PA	Cubic	.867	.049	-8.70	2.03	0.00	-0.01
	L	Cubic	.867	.048	-8.44	2.03	0.00	-0.01
PSS-G2	**FS-M**	Linear	.863	.007	-3.30	26.20		
Chinese	**FS-M**	Linear	.725	.031	-2.78	23.25		
	SFS-M	Inverse	.701	.038	4.274	-.063		
German (without sufferers)	**FS-M**	Linear	.968	.000	-4.16	32.40		
	SFS-M	Linear	.841	.010	-4.43	288.89		

4.4 Discussions

As mentioned in the beginning, it needs quite a lot of time and is relative expensive to make subjective evaluation listening tests to investigate the subjective feelings caused by LFN (for example, annoyance and loudness). Therefore, using calculable or measureable objective parameters to predict people's perception and reaction on this particular noise type is very important and necessary. The first part of this chapter was the introduction of the considered psychoacoustic parameters, which included the definitions, model methods, and also the used settings in the ArtemiS software. Then the correlation, classification and NMDS results obtained from SPSS were compared with the data from Chapter 3. A scaled-down list of the psychoacoustic parameters was made, which were supposed having a stronger relationship with SAV and the evaluated loudness results. After that, the correlation calculation was made for the earlier listening tests to find out more precise relations between psychoacoustic parameters and subjective feelings caused by LFN related signals. The following conclusions were mainly from the outcomes of the analysis using data in experiment 3.4. The results indicated that FS-M or SFS-M had a positive correlation with SAV, and Imp or Imp-M had negative correlation results with SAV when LFN was combined with PTs in the low frequency ranges. The evaluated loudness was found to have a significant positive correlation with L. And in the indirect method test that LFN was combined with different bandwidth PNs in middle or high frequency ranges. SAV was found significantly and positively correlated with PA, L and S, negatively with FS-M and SFS-M. L, S and FS-M had good correlation results with the evaluated loudness.

Then the regression analyses were performed to find out the possible models using psychoacoustic parameters to predict the subjective feelings caused by LFN related signals. The results indicated that L was the best variable to predict the loudness feeling caused by LFN combined with PT in the low frequency range or with PN in middle or high frequency range. For most subjects the relationship was linear, but for subjects with higher GNS or poor mental performance the regression equation could change to the "Quadratic" type. The only special situation was for LFN sufferers when bandwidth PN was the additional component. There was no significant regression type found for them. The regression results for SAV showed that generally PA was suitable to predict the annoyance caused by LFN combined with PN, except for LFN sufferers the better variable was S or Imp. The outcomes from the curve estimation of SAV caused by LFN combined with PT indicated that FS-M was more appropriate than PA to predict the produced annoyance in a linear relation.

Overall, LFN was considered not as a special noise for "normal" subjects. L and PA were designed to simulate human's perception and reaction on loudness and annoyance caused by general noise. And the results obtained from LFN related tests showed that these two psychoacoustic parameters could also well predict the corresponding subjective feelings for the "normal" subjects. But there were quite different results for LFN sufferers, for example, the predicted equation form was different and for some cases there was even no statistical significant perdition for the caused annoyance of loudness. The evidence indicated that the used method to predict the annoyance and loudness perception caused by LFN should be different for LFN sufferers compared with for the "normal" subjects. In addition, there were also differences between GHQ, NS, PSS groups, which proved the hypothesis that personality traits also had influence on perception and reaction caused by LFN.

The obtained conclusions suggest that when LFN is the noise type in an investigation, it is possible to use psychoacoustic loudness to predict the perceived loudness level, and use psychoacoustic annoyance (PA) combined with questionnaires about subject's noise sensitive situation, mental performance and stress level to predict how annoying the subject feels in a positive linear form. Particularly, FS can be a good predictor for annoyance when the investigated LFN is with tonal character. But when the subject is identified or known as LFN sufferers or has high sensitivity for LFN, they should no longer be considered as "normal" and the corresponding method to predict their subjective feelings caused by LFN should be changed.

5 Conclusions and future works

5.1 Conclusions

The described subjective listening tests and EEG experiments confirmed that when people were under the exposure to LFN related signals, their brain would give corresponding reactions mainly based on their experiences, preferences and personality traits, which could be represented by the questionnaires about noise sensitivity, mental performance, emotional situation and stress level, etc. When simulating this process, the input variable was LFN related signals which had different controllable and measureable features, and the output results were the subjective feelings such as annoyance and loudness studied in this work which could be quantified with different methods. Between those were the personality traits and brain reactions. The first one could be measured with questionnaires and used as filters to classify the subjects into different types, the latter was proven feasible to obtain in many forms, and for example, EEG was the used form in this study.

All results from the listening tests and the EEG measurements could be summarized in three aspects, which were between LFN and the caused subjective feelings, LFN and EEG variation, and the subjective feelings and EEG changing. The personality traits were found having different functions in each aspect. The indirect method using Chinese as subjects and adding different bandwidth PNs or WNs to LFN showed effect on reducing the annoyance caused by LFN, and the frequency range and level of the additional component could let the effect differ. The subjects with high GNS evaluated the signals less annoying when PN was combined with LFN and more annoying when WN was used. PN in 20 dB was found having a better result for them. The type and level of the additional component was not statistically different for subjects with normal GNS. The other indirect method test which was made with German subjects indicated that this method could be more suitable for subjects with a slight hearing problem, or relative poor mental performance or for female subjects to reduce their annoyance caused by LFN. PN with the starting frequency near the decreasing position of LFN fitted this method better. There was no significant difference between Chinese and German subjects using this method to decrease their annoyance caused by LFN. In addition, adding extra PN could also decrease the loudness and this effect was found for LFN sufferers and subjects with a relative high stress level.

The brain reactions to the exposures of LFN and PN in the same level were found differently at the Temporal lobe, which was presumed due to their different spectral characters. And adding bandwidth PN in different frequency ranges could also cause different brain reactions, which were presented by the PSD variation. The brain reaction was found to be individual among subjects. Further, differences of various degrees occurred between subjects classified into different questionnaire groups. And the most obvious were found between LFN sufferers and the reference group.

Then the significant relations between EEG results and the annoyance evaluation results were obtained, which gave the evidence for the feasibility of using EEG as the tool to observe the brain reactions to LFN related signals. In general, when there was only LFN related auditory stimuli, the caused subjective annoying value (SAV) had positive correlation with RPSD of θ band at T3 and T5 which belonged to the brain function area of dealing with auditory stimuli. SAV was also found in negative relation with RPSD of β at T5, T6, and F4, which were the function areas for emotional content and auditory imagery. When there were signals comprised of LFN and related visual stimulus, but LFN was the main component for the annoyance reaction, besides the above relationships, SAV was also found in positive correlation with RPSD of θ1 at AF4, α at AF3 and AF4, in where it had the function of processing emotional stimuli. In addition, personality traits showed a certain degree of effect on the correlation results between RPSD and SAV. In the test about the annoyance caused by WTN and WT, the positive relation between SAV and RPSD of θ at O2 was particularly found for subjects with a slight hearing problem, and also for subjects with high GNS plus male subjects. O2 was the electrode position related to the visual stimuli processing, which indicated that the visual information about WT in the signals could cause relative stronger reactions for these subjects.

Some obvious differences were found between LFN sufferers and the reference group. The negative correlation results for SAV with RPSD of θ band at FP2 and AF3 which had the response for emotional stimuli processing, and at C5 which had the function for basic processing of auditory stimuli, were only found for LFN sufferers. Also RPSD of α band at FC5 and FC3, which had the selective to sounds function, showed positive relation with SAV for them. The correlating results between SAV and RPSD of α band at Temporal lobe, Occipital lobe and Parietal lobe were positive for LFN sufferers, and were negative for the reference group. And for β band the main difference was found at the temporal area. It had a positive relation with SAV for LFN sufferers and negative for the reference group. All findings indicated that LFN sufferers had different reactions caused by LFN related signals, particularly presented for cerebral cortex areas that dealt with auditory stimuli and emotional content. This outcome could explain why LFN sufferers always showed different reactions to LFN compared with normal subjects.

The other part of this study was using psychoacoustic parameters as variables to simulate and predict subjective feelings caused by LFN related signals. The findings showed that the evaluated loudness caused by LFN combined with PT in low frequency range or PN in middle or high frequency range could be predicted well with the psychoacoustic loudness (L) for subjects who had normal GNS or normal mental performance, or who were not sensitive to LFN. The predicted relation was positive and linear, which meant that the larger L obtained from LFN related signals the louder the signals could be felt. For the other subjects who had higher GNS or LFNS, or a relatively poor mental situation their loudness feeling could be predicted by L but with a quadratic-formed model. The only exception was the predicted outcome of the evaluated loudness caused by LFN combined with PN for LFN sufferers that there was no significant result. The predicting results for SAV were various. For most subjects the SAV caused by LFN combined with PN could be predicted with a linear model using PA as the variable, and for LFN sufferers the predicting relation was also linear but with S as the parameter. The SAV predicting model for LFN combined with PT was significant with FS-M as the parameter, and the relation was also linear. Noticeably, there was no significant result for LFN sufferers either.

In theory the extra subjective feelings were supposed to have simple and direct relation with the added parts, which meant that the total annoyance or evaluated loudness should be the combination of the original LFN and the additional components. This hypothesis was performed well with the consistent result between the evaluated loudness and L, or for SAV with PA or FS-M for most subjects. However, for LFN sufferers the added PT could also change their total annoyance, but there was no clear prediction rule for them with a single psychoacoustic parameter as the variable. This result was assumed because LFN sufferers had either no obvious low frequency sensitive preference, or they were too sensitive to the low frequency which caused difficulty for them to determine the annoying level. The difference of the effect caused by the added PN for LFN sufferers was that their annoyance or loudness called forth by the combination noise didn't follow the supposed "regular" trend.

And the effect due to the added PN was different for LFN sufferers that their annoyance or loudness caused by the combination noise didn't follow the supposed "regular" trend. It could be explained by the frequency character of the added PN that the original LFN had a more balanced spectrum and a more flattened envelope because of the additional component, which didn't simply make a "linear" or "overlap" function to the total annoyance or loudness for LFN sufferers. In the other words, the indirect method which used additional PN in middle or high frequency range to reduce the negative feelings caused by LFN could be more suitable for LFN sufferers or subjects with high noise sensitivity.

5.2 Future works

Considering the analyses and results obtained from the listening tests, EEG measurements and prediction calculations, the following aspects should be investigated in the future:

- The studies about LFN sufferers

There were only three LFN sufferers in this study, although according to the early finding that the part of the population who were reported complainants about LFN and identified as LFN sufferers is small, a relatively large amount of these special subjects could be better to obtain more general and precise results. For example, it could help investigate the character of their hearing threshold in low, middle and high frequency range. The experimental method used was passive, so it is necessary to utilize more active way like asking the subjects to adjust themselves about the types, frequency ranges and levels of the added components to achieve the annoyance reduction effect, and then to compare with their personal traits to obtain more specific results.

- The difference between Chinese and German subjects

The obtained results indicated that there could be different perceptions and reactions to LFN related signals between Chinese and German subjects. However, since the main purpose of this study was not about finding the difference, it was designed with a large amount of subjects of different nationalities. Therefore, it could be an interesting direction to investigate whether there were differences between them due to the different cultures, living environments, construction of the surrounding noise, etc., particularly, to find whether there are different types of components which could be used in the indirect method to reduce the annoyance or other negative effects caused by LFN.

- The observation of brain reaction to LFN

EEG was proven feasible to observe the brain reactions to LFN related signals. But a certain degree of inconvenience was found during the analysis of the EEG data that the visuality of EEG measurement was weak, and it was difficult to obtain the results during the recording and needed calculation afterward. Therefore, finding other possible means, which could more directly observe the corresponding brain changing due to LFN, could help find the difference between LFN sufferers and the normal subjects and also understand LFN sufferers better.

- Predicting and evaluation methods for LFN sufferers

The results of the Chapter 4 give the evidence that it is possible to use psychoacoustic parameters to predict the annoyance and loudness caused by LFN related signals, and LFN could be treated as other noise types for normal subjects. Therefore, future works can follow this direction to find other parameters which are easy to measure and predict the negative effects caused by LFN. The non-significant predicting results for LFN sufferers means that it requires more attention and investigations to establish special evaluation standard for them. During the analysis, Fluctuation Strength (FS) showed an important function for the prediction of annoyance caused by LFN related signals. This parameter is a part of PA, but perhaps it has different weight in the equation when PA is used to predict the annoyance caused by LFN for the sufferers. A better prediction model could be a multi-dimensional model with the right mixture and weight of some psychoacoustic parameters.

There are also research directions such as the coping strategies against LFN for LFN sufferers, and the most important purpose is to help people to improve their living quality.

Reference

Adams, M., Moorhouse, A., and Waddington, D. (**2007**). "*Social Effects of Low Frequency Noise Exposure on Sufferers: Developing a Procedure of Assessment,*" J. Low Freq. Noise, Vib. Act. Control, 26, 271–282.

Adjouadi, M., Cabrerizo, M., Yaylali, I., and Jayakar, P. (**2004**). "*Interpreting EEG functional brain activity,*" IEEE Potentials, 23, 8–13.

Akita, T., Fujii, T., Hirate, K., and Yasuoka, M. (**1995**). "*A research on auditory information processing in the brain when a person is at his task by means of measurement and analysis of auditory evoked potential,*" J. Archit. Plan. Environ. Eng., 507, 61–69.

Altenmüller, E., Schürmann, K., Lim, V. K., and Parlitz, D. (**2002**). "*Hits to the left, flops to the right: different emotions during listening to music are reflected in cortical lateralisation patterns,*" Neuropsychologia, 40, 2242–2256.

Altmsoy, E., Kanca, G., and Belek, H. T. (**1999**). "*A comparative study on the sound quality of wet and dry type vacuum cleaners,*" 6th Int. Congr. Sound Vib., Copenhagen, Denmark.

Aylor, D. E. (**1976**). "*Perception of noise transmitted through barriers,*" J. Acoust. Soc. Am., 59, 397.

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., and Bouma, J. (**2012**). "*Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress,*" Sci. Total Environ., 425, 42–51.

Banich, M. (**1997**). "*Neuropsychology: The Neural Bases of Mental Function,*" Houghton Mifflin.

Belojević, G., Öhrström, E., and Rylander, R. (**1992**). "*Effects of noise on mental performance with regard to subjective noise sensitivity,*" Int. Arch. Occup. Environ. Health, 64, 293–301.

Bengtsson, J. (**2003**). *Low frequency noise during work effects on performance and annoyance* University of Gothenburg, M1 - Doctoral thesis.

Benton, S., and Leventhall, H. G. (**1986**). "*Experiments into the impact of low level, low frequency noise upon human behavior,*" J. Low Freq. Noise, Vib. Act. Control, 5, 143–162.

Benton, S., and Robinson, G. (**1993**). "*The effects of noise on text problem solving for the word processor user (WPU),*" Proc. 6th Int. Congr. Noise as a Public Heal. Probl., France.

Beranek, L. L. (**1989**). "*Balanced noise-criterion (NCB) curves,*" J. Acoust. Soc. Am.,.

Beranek, L. L., Blazier, W. E., and Figwer, J. J. (**1971**). "*Preferred Noise Criterion (PNC) Curves and Their Application to Rooms,*" J. Acoust. Soc. Am.,.

Berglund, B., and Lindvall, T. (**1995**). *Community Noise* World Heal. Organ.,World Health Organization, 146 pages.

Blazier, W. E. (**1981**). "*Revised noise criteria for application in the acoustic design of and rating of HVAC systems,*" Noise Control Eng, 16, 64–73.

Borsky, P. N. (**1980**). "*Review of community response to noise,*" Proc. noise as a public Heal. Probl., Rockville, 453–474.

Bowdler, R., and Leventhall, G. (**2014**). "*Wind Turbine Noise,*" Multi-Science Publishing Co Ltd.

Branco, N. A. A. C., and Alves-Pereira, M. (**2004**). "*Vibroacoustic disease,*" Noise Health, 6, 3–20.

Brodmann, K. (**1909**). "*Vergleichende Lokalisationslehre der Großhirnrinde: in ihren Prinzipien dargestellt auf Grund des Zellenbaues,*" Leipzig.

Broner, N. (**1978**). "*The effects of low frequency noise on people - A review,*" J. Sound Vib., 58, 483–500. Retrieved from http://www.sciencedirect.com/science/article/pii/0022460X78903541

Broner, N., and Leventhall, H. G. (**1978**). "*Individual annoyance functions,*" Acoust. Lett., 2, 22–25.

Broner, N., and Leventhall, H. G. (**1983**). "*Low frequency noise annoyance assessment by Low Frequency Noise Rating Curves,*" J. Low Freq. Noise Vib. Act. Control, 2, 20–28.

Bryan, M. E. (**1976**). "*Low frequency noise annoyance. In: Infrasound and Low Frequency Vibration,*" (W.Tempest, Ed.) Academic Press.

Chai, W. (**2012**). *Cortical functions*.

Challis, L. A., and Challis, A. M. (**1978**). "*Low frequency noise problems from gas turbine power stations,*" Proc Internoise, Proc Internoise, San Francisco, USA.

Chatrian, G. E., Lettich, E., and Nelson, P. L. (**1985**). "*Ten percent electrode system for topographic studies of spontaneous and evoked EEG activity,*" Am. J. EEG Technol., 25, 83–92.

Cho, W., Hwang, S.-H., and Choi, H. (**2011**). "*An investigation of the influences of noise on EEG power bands and visual cognitive responses for human-oriented product design,*" J. Mech. Sci. Technol., 25, 821–826.

Department for Environment Food and Rural Affairs (**2009**). *Development of a course in computerised Cognitive Behavioural Therapy aimed at relieving the problems of those suffering from noise exposure, in particular, exposure to low frequency noise (NANR 237).*

Dhiman, R., Saini, J. S., and Mittal, A. P. (**2010**). "*Artifact removal from EEG recordings- an overview,*" NCCI 2010- Natl. Conf. Comput. Instrum., Chandigarh, India.

Di, G., Li, Z., Zhang, B., and Shi, Y. (**2011**). "*Adjustment on subjective annoyance of low frequency noise by adding additional sound,*" J. Sound Vib., 330, 5707–5715.

DIN45680 (**1997**). *DIN 45680.*

Evans, G. W. (**1982**). "*Environmental Stress,*" Handb. Environ. Psychol.,.

Fastl, H., and Zwicker, E. (**2007**). "*Psychoacoustics - Facts and Models,*" Springer-Verlag

Berlin Heidelberg.

Fields, J. M. (**1993**). "*Effect of personal and situational variables on noise annoyance in residential areas,*" J. Acoust. Soc. Am., 93, 2753.

G.P. van den Berg (**1999**). "*Assessment of low frequency noise complaints,*" Proc Internoise, Fort Lauderdale, Florida, USA.

Gelfand, S. A. (**2009**). "*Hearing- An introduction to psychological and physiological acoustics,*" Informa Healthcare.

Genell, A., Västfjäll, D., Kleiner, M., and Hedlund, A. (**2006**). "*Components in evaluation of complex interior truck sounds,*" J. Low Freq. Noise, Vib. Act. Control, 25, 227–237.

Goldberg, D. P., and Hillier, V. F. (**1979**). "*A scaled version of the General Health Questionnaire,*" Psychol. Med., 9, 139–145.

Guski, R. (**1999**). "*Personal and social variables as co-determinants of noise annoyance,*" Noise Health, 1, 45–56.

Guski, R., Felscher-Suhr, U., and Schuemer, R. (**1999**). "*The concept of noise annoyance: How international experts see it,*" J. Sound Vib., 223, 513–527.

Gyslain Giguère (**2006**). "*Collecting and analyzing data in multidimensional scaling experiments : A guide for psychologists using SPSS,*" Tutor. Quant. Methods Psychol., 2, 26–37.

Hallmann, S., Guski, R., and Schuemer, R. (**2002**). "*What residents have in mind when asked for scaling noise annoyance,*" Proc. 2002 Int. Congr. Expo. Noise Control Eng., Proceedings of the 2002 International Congress and Exposition on Noise Control and Engineering, USA.

Hayashi, T., Okamoto, E., Nishimura, H., Mizuno-Matsumoto, Y., Ishii, R., and Ukai, S. (**2009**). "*Beta Activities in EEG Associated with Emotional Stress,*" Int. J. Intell. Comput. Med. Sci. Image Process., 3, 57–68.

He, M., Deng, Z., and Krahé, D. (**2014**). "*The subjective influence of the LFN combined with pink and white noise,*" 40th Annu. Ger. Congr. Acoust., 40th Annual German Congress on Acoustics (DAGA), Oldenburg, Germany.

HEAD Acoustics (**2013**). *Psychoacoustic Analyses I.*

HEAD Acoustics (**2014**). *Psychoacoustic Analyses II.*

Inukai, Y., Nakamura, N., and Taya, H. (**2000**). "*Unpleasantness and acceptable limits of low frequency sound,*" J. Low Freq. Noise, Vib. Act. Control, 19, 135–140.

Inukai, Y., Taua, H., Utsugi, A., and Nagamur, N. (**1990**). "*A new evaluation method for low frequency noise,*" Proc Internoise, Göteborg, Sweden.

Inukai, Y., Taya, H., and Yamada, S. (**2005**). "*Thresholds and acceptability of low frequency pure tones by sufferers,*" J. Low Freq. Noise, Vib. Act. Control, 24, 163–169.

Ising, H., and Ising, M. (**2002**). "*Chronic Cortisol Increases in the First Half of the Night Caused by Road Traffic Noise,*" Noise Health, 4, 13–21.

Jakobsen, J. (**2001**). "*Danish guidelines on environmental low frequency noise, infrasound and vibration,*" J. Low Freq. Noise, Vib. Act. Control, 20, 141–148.

Jasper, H. H. (**1958**). "*The 10-20 electrode system of the International Federation,*" Electroen Clin Neuro, 10, 370–375.

Job, R. F. S. (**1988**). "*Community response to noise: A review of factors influencing the relationship between noise exposure and reaction,*" J. Acoust. Soc. Am., 83, 991.

Job, R. F. S. (**1999**). "*Noise sensitivity as a factor influencing human reaction to noise,*" Noise Health, 1, 57–68.

Johansson, M., and Laike, T. (**2007**). "*Intention to respond to local wind turbines: the role of attitudes and visual perception,*" Wind Energ. Wind Energy, 10, 435–451.

Julie Onton (**2010**). "*Artifact rejection and running ICA,*" 11th EEGLAB Work. NCTU, Taiwan.

Jung, T. P., Makeig, S., Humphries, C., Lee, T. W., McKeown, M. J., Iragui, V., and Sejnowski, T. J. (**2000**). "*Removing electroencephalographic artifacts by blind source separation,*" Psychophysiology, 37, 163–78.

Jung, T.-P., Humphries, C., Lee, T.-W., Makeig, S., McKeown, M. J., Iragui, V., and Sejnowski, T. J. (**1998**). "*Extended ICA Removes Artifacts from Electroencephalographic Recordings,*" Adv. Neural Inf. Process. Syst., Cambridge, MA, US.

Kabuto, M., Kageyama, T., and Nitta, H. (**1993**). "*EEG power spectrum changes due to listening to pleasant music and their relation to relaxation effects,*" Nihon Eiseigaku Zasshi., 48, 807–818.

Kandel, E. R., Schwartz, J., and Jessell, T. (**2000**). "*Principles of Neural Science,*" McGraw-Hill Medical.

Kasprzak, C. (**2014**). "*The influence of infrasound noise from wind turbines on EEG signal patterns in humans,*" ACTA Phys. Poloica A, 125, 20–23.

Kastka, J. an., and Hangartner, M. (**1986**). "*Machen hässliche Strassen den Verkehrslärm lästiger ? [Do ugly streets increase road traffic noise annoyance?],*" Arcus, 1, 23–29.

Kjellberg, A., Goldstein, M., and Gamberale, F. (**1984**). "*An assessment of dBA for predicting loudness and annoyance of noise containing low frequency components,*" J. Low Freq. Noise, Vib. Act. Control, 3, 10–16.

Kjellberg, A., and Wide, P. (**1988**). "*Effects of simulated ventilation noise on performance of a grammatical reasoning task,*" Proc. 5th Int. Congr. Noise as a Public Heal. Probl., Stockholm, Sweden, 31–36.

Kosten, C. W., and VanOs, G. J. (**1962**). "*Community reaction criteria for external noises,*" NPL Symp. Control Noise, 12, 373–387.

Krahé, D. (**2010**). "*Low frequency noise- strain on the brain,*" 14th Int. Meet. Low Freq. Noise Vib. its Control, Aalborg, Denmark.

Krahé, D. (**2012**). "*What makes low-frequency noise annoying,*" Proc Internoise, New York City, USA.

Kruskal, J. B., and Wish, M. (**1978**). "*Multidimensional scaling,*" Beverly Hills, CA.

Kurakata, K., Mizunami, T., Sato, H., and Inukai, Y. (**2008**). "*Effect of Ageing on Hearing Thresholds in the Low Frequency Region,*" J. Low Freq. Noise, Vib. Act. Control, 27, 175–184.

Kuwano, S., Namba, S., Hashimoto, T., Berglund, B., Rui, Z. Da, Schick, A., Hoege, H., et al. (**1991**). "*Emotional expression of noise: A cross-cultural study,*" J. Sound Vib., 151, 421–428.

Kwan ryu, J., Sato, H., Kurakata, K., and Yukio (**2008**). "*Effects of low frequency sound on subjective response in real living environments using autocorrelation function and psychoacoustical parameters,*" Inter-noise 2008,.

Landström, U., Byström, M., and Nordström, B. (**1985**). "*Changes in wakefulness during exposure to noise at 42Hz, 1000Hz and individual EEG frequencies,*" J. Low Freq. Noise Vib., 4, 27–33.

Landström, U., Kjellberg, A., and Söderberg, L. (**1991**). "*Spectral character, exposure levels and adverse effects of ventilation noises in offices,*" J. Low Freq. Noise, Vib. Act. Control, 10, 83–91.

Landström, U., Kjellberg, A., Söderberg, L., and Nordström, B. (**1992**). "*The effects of broadband, tonal and masked ventilation noise on performance, wakefulness and annoyance,*" J. Low Freq. Noise, Vib. Act. Control, 10, 112–122.

Langdon, F. J. (**1976**). "*Noise nuisance caused by road traffic in residential areas: Part II,*" J. Sound Vib., 47, 265–282.

Larsen, E. A. (**2011**). *Classification of EEG signals in a brain-computer interface system* Norwegian University of Science and Technology, M1 - Master.

Lee, J. S. Y., J.Hautus, M., and Shepherd, D. (**2012**). "*Neural correlates of noise annoyance and sensitivity,*" Proc. 21st Bienn. Conf. Acoust. Soc. New Zeal., Wellington, New Zealand.

Leventhall, G. (**2009**). "*Low Frequency Noise What we know, what we do not know, and what we would like to know,*" J. Low Freq. Noise, Vib. Act. Control, 28, 79–104.

Leventhall, G., Benton, S., and Robertson, D. (**2008**). "*Coping Strategies for Low Frequency Noise,*" J. Low Freq. Noise, Vib. Act. Control, 27, 35–52.

Leventhall, G., Pelmear, P., and Benton, S. (**2003**). *A review of published research on low frequency noise and its effects* Department for Environment, Food and Rural Affairs.

Leventhall, H. G. (**1998**). "*Making noise comfortable for people,*" Transactions, 104, 896–900.

Leventhall, H. G. (**2004**). "*Low frequency noise and annoyance,*" Noise Health, 6, 59–72.

Li, Z.-G. (**2012**). *Study on acoustical simulation and adjustment methods of subjective perception and objective law of electroencephalogram variation under noise exposure* Zhejiang University, M1 - PhD.

Li, Z.-G., Di, G.-Q., and Jia, L. (**2014**). "*Relationship between Electroencephalogram variation and subjective annoyance under noise exposure,*" Appl. Acoust., 75, 37–42.

M. Ungureanu, Bigan, C., Strungaru, R., and Lazarescu, V. (**2004**). "*Independent Component Analysis applied in biomedical signal processing,*" Meas. Sci. Rev.,.

M. Willemsen, A. ;, and D. Rao, M. (**2010**). "*Characterization of sound quality of impulsive sounds using loudness based metric,*" Proc. 20th Int. Congr. Acoust. ICA 2010, Sydney, Australia.

Makeig, S., Bell, A. J., Jung, T., and Sejnowski, T. J. (**1996**). "*Independent Component Analysis of Electroencephalographic Data,*" Adv. Neural Inf. Process. Syst., MIT Press, pp. 145–151.

Matsumura, Y., and Rylander, R. (**1991**). "*Noise sensitivity and road traffic annoyance in a population sample,*" J. Sound Vib., 151, 415–419.

MEP (**2011**). *China Environmental Noise Prevention and Control Annual Report.*

Mirowska, M. (**2003**). "*Problems of Measurement and Evaluation of Low-Frequency Noise in Residential Buildings in the Light of Recommendations and the New European Standards,*" J. Low Freq. Noise, Vib. Act. Control, 22, 203–208.

Møller, H. (**1987**). "*Annoyance of audible infrasound,*" J. Low Freq. Noise, Vib. Act. Control, 6, 1–17.

Moorhouse, A., Waddington, D., and Adams, M. (**2005**). *Proposed criteria for the assessment of low frequency noise disturbance* Department for Environment, Food and Rural Affairs.

Moreira, N. M., and Bryan, M. E. (**1972**). "*Noise annoyance susceptibility,*" J. Sound Vib., 21, 449–462.

Müller, N., Keil, J., Obleser, J., Schulz, H., Grunwald, T., Bernays, R.-L., Huppertz, H.-J., et al. (**2013**). "*You can't stop the music: reduced auditory alpha power and coupling between auditory and memory regions facilitate the illusory perception of music during noise,*" Neuroimage, 79, 383–93.

Nagai, N., Matsumoto, M., and Yamasumi, Y. (**1989**). "*Process and emergence on the effects of infrasonic and low frequency noise on inhabitants,*" J. Low Freq. Noise Vib., 8, 87–99.

Nagyova, I., Krol, B., Szilasiova, A., Stewart, R. E., van Dijk, J. P., and van den Heuvel, W. J. A. (**2000**). "*General health questionnaire-28- psychometric evaluation of the Slovak version,*" Stud. Psychol. (Bratisl)., 42, 351–361.

Nakamura, N., and Inukai, Y. (**1998**). "*Proposal of models which indicate unpleasantness of low frequency noise using exploratory factor analysis and structural covariance analysis,*" J. Low Freq. Noise, Vib. Act. Control, 17, 127–132.

Nijland, H. A., Hartemink, S., van Kamp, I., and van Wee, B. (**2007**). "*The influence of sensitivity for road traffic noise on residential location: does it trigger a process of spatial selection?,*" J. Acoust. Soc. Am., 122, 1595.

NSG (**1999**). "*NSG-Richtlijn Laagfrequent Geluid.,*"

Nykänen, A., and Sirkka, A. (**2009**). "*Specification of component sound quality applied to automobile power windows,*" Appl. Acoust., 70, 813–820.

Ochoa, J. B. (**2002**). *EEG signal classification for brain computer interface applications* Ecole

Polytechnique Federale de Lausanne.

Oldfield, R. C. (**1971**). "*The assessment and analysis of handedness: The Edinburgh inventory,*" Neuropsychologia, 9, 97–113.

Otto, N., Amman, S., Eaton, C., and Lake, S. (**2001**). "*Guidelines for Jury Evaluations of Automotive Sounds,*" J. Sound Vib., 35, 24–47.

Oud, M. (**2012**). "*Low-frequency noise: a biophysical phenomenon,*" Noise, Vib. Air Qual. F. Build., Noise, Vibration, Air Quality, and Field & Building, Netherlans.

Park, K. S., Choi, H., Lee, K. J., Lee, J. Y., An, K. O., and Kim, E. J. (**2011**). "*Patterns of electroencephalography (EEG) change against stress through noise and memorization test,*" Int. J. Med. Med. Sci.,.

Pawlaczyk-Luszcynska, M., Dudarewicz, A., and Waszkowska, M. (**2002**). "*Annoyance of low frequency noise in control rooms,*" Proc. Int. Congr. Expo. Noise Control Eng., Proceedings of the International Congress and Exposition on Noise Control and Engineering, Mi. USA.

Pawlaczyk-Luszczynska, M., Dudarewicz, A., Waszkowska, M., and Sliwinska-Kowalska, M. (**2009**). "*Annoyance Related to Low Frequency Noise in Subjective Assessment of Workers,*" J. Low Freq. Noise, Vib. Act. Control, 28, 1–17.

Pedersen, C. S., and Marquardt, T. (**2009**). "*Individual differences in low-frequency noise perception,*" Proc Internoise, Ottawa, Canada.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "*Response to noise from modern wind farms in The Netherlands,*" J. Acoust. Soc. Am., 126, 634–643.

Pedersen, E., and Larsman, P. (**2008**). "*The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines,*" J. Environ. Psychol., 28, 379–389.

Pedersen, E., and Persson, W. K. (**2007**). "*Wind turbine noise, annoyance and self-reported health and well-being in different living environments,*" Occup Env. Med, 64, 480–486.

Pedersen, E., and Waye, K. P. (**2004**). "*Perception and annoyance due to wind turbine noise--a dose-response relationship,*" J. Acoust. Soc. Am., 116, 3460–3470.

Penton, S., and Chin-Quee, D. (**2002**). "*Current low frequency noise (LFN) assessment guidelines and their use in environmental noise impact assessment,*" Can. Acoust., 30, 78–79.

Persson, K., Bjorkman, M., and Rylander, R. (**1985**). "*An experimental evaluation of annoyance due to low frequency noise,*" J. Low Freq. Noise, Vib. Act. Control, 4, 145–153.

Persson, K., Bjorkman, M., and Rylander, R. (**1990**). "*Loudness, annoyance and the dBA in evaluating low frequency sounds,*" J. Low Freq. Noise, Vib. Act. Control, 9, 32–45.

Persson Waye, K. (**1995**). *On the effects of environmental low frequency noise* Gothenburg University, M1 - PhD.

Persson Waye, K., Bengtsson, J., Kjellberg, A., and Benton, S. (**2001**). "*Low frequency noise 'pollution' interferes with performance,*" Noise Health, 4, 33–49.

Persson Waye, K., Rylander, R., Benton, S., and Leventhall, H. G. (**1997**). "*Effects on performance and work quality due to low frequency ventilation noise,*" J. Sound Vib., 205, 467–474.

Poulsen, T. (**2003**). "*Annoyance of low frequency noise in the laboratory assessed by LFN-sufferers and non-sufferers,*" J. Low Freq. Noise, Vib. Act. Control, 22, 191–201.

Poulsen, T., and Mortensen, F. R. (**2002**). *Laboratory evaluation annoyance of low frequency noise* Denmark.

R. Sottek (**1994**). "*Gehörgerechte Rauhigkeitsberechnung (in German),*" Proc. DAGA '94, Dresden, Germany, 1197–1200.

Ray, W. J., and Cole, H. W. (**1985**). "*EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes,*" Science, 228, 750–2.

Ryu, J. K., and Jeon, J. Y. (**2011**). "*Influence of noise sensitivity on annoyance of indoor and outdoor noises in residential buildings,*" Appl. Acoust., 72, 336–340.

Saeid Sanei, and J.A. Chambers (**2007**). "*EEG signal processing,*" John Wiley & Sons Ltd,.

Saito, K. (**1988**). "*Effect of noise on higher nervous activity,*" J. Sound Vib., 127, 419–424.

Salt, A. N., and Lichtenhan, J. T. (**2011**). "*Responses of the inner ear to infrasound,*" Fourth Int. Meet. Wind Turbine Noise, Fourth International Meeting on Wind Turbine Noise, Italy.

Salt, A. N., and Lichtenhan, J. T. (**2012**). "*Perception-based protection from low-frequency sound may not be enough,*" Proc Internoise, Proceedings InterNoise, New York City, USA.

Samaneh Valipour, and Shaligram, A. D. (**2014**). "*Detection of an Alpha Rhythm of EEG Signal Based On EEGLAB,*" Int. J. Eng. Res. Appl., 4, 154–159.

Schick, F. (**1994**). "*The Helicotrema and the Frequency Resolution in the Inner Ear,*" Acustica, 80, 463–470.

Schmidt, L. A., and Trainor, L. J. (**2001**). "*Frontal brain electrical activity(EEG) distinguishes valence and intensity of musical emotions,*" Cogn. Emot., 15, 487–500.

Schutte, M., Marks, A., Wenning, E., and Griefahn, B. (**2007**). "*The development of the noise sensitivity questionnaire,*" Noise Health, 9, 15–24.

Seo, S.-H., and Lee, J.-T. (**2010**). "*Stress and EEG,*" In Marius Crisan (Ed.), Converg. Hybrid Inf. Technol., Intech, pp. 413–426.

Sheldon, C., Kamarck, T., and Mermelstein, R. (**1983**). "*A Global Measure of Perceived Stress,*" J. Health Soc. Behav., 24, 385–396.

Shepherd, D., Welch, D., Dirks, K. N., and Mathews, R. (**2010**). "*Exploring the relationship between noise sensitivity, annoyance and health-related quality of life in a sample of adults exposed to environmental noise,*" Int. J. Environ. Res. Public Health, 7, 3579–3594.

Sloven, P. (**2000**). "*Structured approach of lfn-complaints in the Rotterdam region,*" Proc., 9th Int. Meet. Low Freq. Noise Vib., Proc., 9th Int. Meeting on Low Frequency Noise and Vibration, Aalborg, Denmark.

Socialstyrelsen-Sweden (**1996**). *SOSFS 1996:7/E Indoor Noise and High Sound Levels.*

Solomon, G. E. (**1983**). "*Electroencephalography: Basic principles, clinical applications and related fields,*" Ann. Neurol., 14, 96–96.

Sottek, R., and Genuit, K. (**2007**). "*Sound quality evaluation of fan noise based on hearing-related parameters,*" Proc. Fan Noise 2007, Lyon, France.

Stansfeld, S. A. (**1992**). "*Noise, noise sensitivity and psychiatric disorder: epidemiological and psychophysiological studies,*" Psychol. Med. Monogr. Suppl., 22, 1–44.

Stenberg, G. (**1992**). "*Personality and the EEG: Arousal and emotional arousability,*" Pers. Individ. Dif., 13, 1097–1113.

Sutton, S. K., and Davidson, R. J. (**2000**). "*Prefrontal brain electrical asymmetry predicts the evaluation of affective stimuli,*" Neuropsychologia, 38, 1723–1733.

Tachibana, H., Yano, H., Fukushima, A., and Sueoka, S. (**2014**). "*Nationwide field measurements of wind turbine noise in Japan,*" Noise Control Eng. J., 62, 90–101.

Taylor, S. M. (**1984**). "*A path model of aircraft noise annoyance,*" J. Sound Vib., 96, 243–260.

Tempest, W. (**1989**). "*A survey of low frequency noise complaints received by local authorities in the United Kingdom,*" J. Low Freq. Noise, Vib. Act. Control, 8, 45–49.

Tesarz, M., Kjellberg, A., Landstrom, U., and Holmberg, K. (**1997**). "*Subjective Response Patterns Related to Low Frequency Noise,*" J. Low Freq. Noise, Vib. Act. Control, 6, 145–150.

Thomas F. Collura (**1997**). "*The Measurement, Interpretation, and Use of EEG Frequency Bands,*" BrainMaster Technol. Inc.,.

Thut, G., Nietzel, A., Brandt, S., and Pacual-Leone, A. (**2006**). "*Alpha-band electroencephalographic (EEG) activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection,*" J. Neurosci.,.

Tsujimura, S., and Akita, T. (**2012**). "*Psychophysiological Experiments on Extent of Disturbance of Noises Under Conditions of Different Types of Brain Works,*" In Daniela Siano (Ed.), Noise Control. Reduct. Cancel. Solut. Eng., Intech.

VandenBerg, G., Pedersen, E., Bouma, J., and Bakker, R. (**2008**). *Project WINDFARM perception- Visual and acoustic impact of wind turbine farms on residents.*

Viinikainen, M., Kätsyri, J., and Sams, M. (**2012**). "*Representation of perceived sound valence in the human brain,*" Hum. Brain Mapp., 33, 2295–305.

Viollon, S., Lavandier, C., and Drake, C. (**2002**). "*Influence of visual setting on sound ratings in an urban environment,*" Appl. Acoust., 63, 493–511.

Vishnubhotla, S., Xiao, J., Xu, B., McKinney, M., and Zhang, T. (**2012**). "*Annoyance perception and modeling for hearing-impaired listeners,*" 2012 IEEE Int. Conf. Acoust. Speech Signal Process., IEEE, 161–164.

Walford, R. E. (**1983**). "*A classification of environmental 'hums' and low frequency tinnitus,*" J. Low Freq. Noise, Vib. Act. Control,.

Walter, W. G., Dovey, V. J., and Shipton, H. (**1946**). "*Analysis of the electrical response of the human cortex to photic stimulation,*" Nature, 158, 540.

Wang, J. L. (**2006**). *Experimental Research of the Effect of the Environmental Noise on Physical and Psychological Parameter (in Chinese)* ChongQing University.

Watson, D., Clark, L. A., and Tellegen, A. (**1988**). "*Development and validation of brief measures of positive and negative affect: the PANAS scales,*" J. Pers. Soc. Psychol., 54, 1063–1070.

Weisz, N., Hartmann, T., Müller, N., Lorenz, I., and Obleser, J. (**2011**). "*Alpha rhythms in audition: cognitive and clinical perspectives,*" Front. Psychol., 2, 73.

Whiterod, M. (**1972**). *Human auditory response to intense infrasound* University of Salford.

Wigram, T. (**1993**). "*Observational research- Case studies in vibroacoustic therapy,*" 7th World Congr. Music Ther., Vitoria, Spain.

Yu, X. G. (**2006**). *The measurement and influence analysis of LFN in air-conditioning system (in Chinese)* Southwest Jiaotong University.

Zhao, J. L. (**2010**). "*Effect of middle and low frequency noise on the health of electricity producing workers (in Chinese),*" Chinese J. Urban Rural Enterp. Hyg., 136, 87–88.

Zhou, J., Liu, D., Li, X., Ma, J., Zhang, J., and Fang, J. (**2012**). "*Pink noise: effect on complexity synchronization of brain activity and sleep consolidation,*" J. Theroretical Biol., 306, 68–72.

Zimmer, K., and Ellermeier, W. (**1998**). "*Konstruktion und Evaluation eines Fragebogens zur Erfassung der individuellen Lärmempfindlichkeit,*" Diagnostica, 44, 11–20.

Appendix

Appendix 1 The used questionnaire tables

- **Edinburgh Handedness Inventory**

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, *put ++*. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets. Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		

- **General health questionnaire (GHQ-28)**

1	Have you recently been feeling perfectly well and in good health?	Better than usual	Same as usual	Worse than usual	Much worse than usual
2	Have you recently been feeling in need of a good tonic?	Not at all	No more than usual	Rather more than usual	Much more than usual
3	Have you recently been feeling run down and out of sorts?	Not at all	No more than usual	Rather more than usual	Much more than usual
4	Have you recently felt that you are ill?	Not at all	No more than usual	Rather more than usual	Much more than usual
5	Have you recently been getting any pains in your head?	Not at all	No more than usual	Rather more than usual	Much more than usual

6	Have you recently been getting a feeling of tightness or pressure in your head?	Not at all	No more than usual	Rather more than usual	Much more than usual
7	Have you recently been having hot or cold spells?	Not at all	No more than usual	Rather more than usual	Much more than usual
8	Have you recently lost much sleep over worry?	Not at all	No more than usual	Rather more than usual	Much more than usual
9	Have you recently had difficulty in staying asleep once you are off?	Not at all	No more than usual	Rather more than usual	Much more than usual
10	Have you recently felt constantly under strain?	Not at all	No more than usual	Rather more than usual	Much more than usual
11	Have you recently been getting edgy and bad-tempered?	Not at all	No more than usual	Rather more than usual	Much more than usual
12	Have you recently been getting scared or panicky for no good reason?	Not at all	No more than usual	Rather more than usual	Much more than usual
13	Have you recently found everything getting on top of you?	Not at all	No more than usual	Rather more than usual	Much more than usual
14	Have you recently been feeling nervous and strung-up all the time?	Not at all	No more than usual	Rather more than usual	Much more than usual
15	Have you recently been managing to keep yourself busy and occupied?	More so than usual	Same as usual	Rather less than usual	Much less than usual
16	Have you recently been taking longer over the things you do?	Quicker than usual	Same as usual	Longer than usual	Much longer than usual
17	Have you recently felt on the whole you were doing things well?	Better than usual	About the same	Less well than usual	Much less than usual
18	Have you recently been satisfied with the way you've carried out your task?	More satisfied	About same as usual	Less satisfied than usual	Much less satisfied
19	Have you recently felt that you are playing a useful part in things?	More so than usual	Same as usual	Less useful than usual	Much less useful
20	Have you recently felt capable of making decisions about things?	More so than usual	Same as usual	Less so than usual	Much less than usual
21	Have you recently been able to enjoy your normal day-to-day activities?	More so than usual	Same as usual	Less so than usual	Much less than usual
22	Have you recently been thinking of yourself as a worthless person?	Not at all	No more than usual	Rather more than usual	Much more than usual
23	Have you recently felt that life is entirely hopeless?	Not at all	No more than usual	Rather more than usual	Much more than usual
24	Have you recently felt that life isn't worth living?	Not at all	No more than usual	Rather more than usual	Much more than usual
25	Have you recently thought of the possibility that you might make away with yourself?	Definitely not	I don't think so	Has crossed my mind	Definitely have
26	Have you recently found at times you couldn't do anything because your nerves were too bad?	Not at all	No more than usual	Rather more than usual	Much more than usual
27	Have you recently found yourself wishing you were dead and away from it all?	Not at all	No more than usual	Rather more than usual	Much more than usual
28	Have you recently found that the idea of taking your own life kept coming into your mind?	Definitely not	I don't think so	Has crossed my mind	Definitely has

- ### General noise sensitivity questionnaire

Very agree	**a little bit agree**	**a little bit disagree**	**disagree**
4	**3**	**2**	**1**

1	I can't block the noise around me.	
2	For the hardest work I need the quietest environment.	
3	When I buy an apartment, I can accept its other bad sides just to get a quiet environment.	
4	I am very sensitive for the noise from the neighbors.	
5	I find that it is very difficult to communicate with the others under a noisy environment.	
6	I can do the normal tasks in a noisy environment.	
7	When I want to sleep, I will be upset if I can hear people talking around me.	
8	When I talk with people with my whole attention, it doesn't affect me a lot whether the environment is very loud.	
9	No matter how loud around me, I can fall asleep.	
10	My work efficiency will be obviously affected by very loud noise.	
11	The loud music will relax me after work.	
12	I can't focus on my conversation, when people talk in a loud voice from the neighboring table in the restaurant.	
13	I can only do new works in a quiet environment.	
14	When people around me all talk very loud, I can't do my job well.	
15	A good sleep for me can only be achieved in a quiet environment.	
16	I can't sleep well no matter how small level is the noise.	
17	I can adapt myself very fast to the noise in the new living environment.	
18	Small talking or the noise from candy wrappers will disturb me in the cinema.	
19	I think the conversation can be interfered by music.	
20	I find that the conversation is hard to continue when the radio is on.	
21	When my working place is very loud, I always want to find a solution to solve it.	
22	I think for dancing, the music should be as loud as possible.	
23	To living in a loud street or not is not important for me.	
24	If the unknown children are very loud, they should definitely not play in front of my apartment.	
25	In the weekend I prefer to have a quiet environment.	
26	If the last night was very loud, in the morning I will feel I didn't sleep enough.	
27	I will feel uncomfortable when the radio behind me at home is very loud.	
28	When the music is very loud in the club, I will stop talking.	
29	I can finish complex work under background music.	
30	Tiny noise can wake me up.	
31	I will avoid having entertainment activities in a very loud place.	
32	I don't like to have entertainment activities in my living area.	
33	I can be interfered by the general noise from neighbors. (such as, go up and down the stairs, or the sound of flowing water)	
34	Even the thunder is very loud, it can't disturb my sleeping.	
35	If the environment is very noisy, I will finish conversation via phone very fast.	

- **Low frequency Noise sensitivity questionnaire**

	do not agree at all				agree completely
I'm sensitive to noise with bass					
I think that monotonous humming (e.g. from a transformer) is unpleasant even it is low level					
I like listening to music with bass turned on					
I am sensitive to rumbling noise from ventilation system					
Are you sensitive to LFN	not at all sensitive	not very sensitive	rather sensitive	very sensitive	extremely sensitive

- **The Positive and Negative Affect Schedule (PANAS)**

This scale consists of a number of words that describe different feelings and emotions. Read each item and then list the number from the scale below next to each word. Indicate to what extent you feel this way right now, that is, at the present moment or indicate the extent you have felt this way over the past week.

		very slightly or not at all	a little	moderately	quite a bit	extremely
1	Interested					
2	Distressed					
3	Excited					
4	Upset					
5	Strong					
6	Guilty					
7	Scared					
8	Hostile					
9	Enthusiastic					
10	Proud					
11	Irritable					
12	Alert					
13	Ashamed					
14	Inspired					
15	Nervous					
16	Determined					
17	Attentive					
18	Jittery					
19	Active					
20	Afraid					

- **The Perceived Stress Scale (PSS)**

The questions in this scale ask you about your feelings and thoughts during the last month. In each case, you will be asked to indicate by circling how often you felt or thought a certain way.

		Never	Almost Never	Sometimes	Fairly often	Very often
1	In the last month, how often have you been upset because of something that happened unexpectedly?					
2	In the last month, how often have you felt that you were unable to control the important things in your life?					
3	In the last month, how often have you felt nervous and stressed”?					
4	In the last month, how often have you felt confident about your ability to handle your personal problems?					
5	In the last month, how often have you felt that things were going your way?					
6	In the last month, how often have you found that you could not cope with all the things that you had to do?					
7	In the last month, how often have you been able to control irritations in your life?					
8	In the last month, how often have you felt that you were on top of things?					
9	In the last month, how often have you been angered because of things that were outside of your control?					
10	In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?					

- **Hearing problem self-test**

1	Do you have a problem hearing on the telephone?	Yes	No
2	Do you have trouble hearing in a noisy environment, such as an auditorium or a busy restaurant?	Yes	No
3	Is it hard for you to follow a conversation when two or more people talk at once?	Yes	No
4	Do you have to strain to understand a conversation?	Yes	No
5	Do many people you talk to seem to mumble (or not speak clearly)?	Yes	No
6	Do you misunderstand what others are saying and respond inappropriately?	Yes	No
7	Do you often ask people to repeat themselves?	Yes	No
8	Do you have trouble understanding the speech of women and children?	Yes	No
9	Do people complain that you turn the TV volume up too high?	Yes	No
10	Do you have to work in noisy environments?	Yes	No
11	Do you miss hearing some common sounds like the telephone or doorbell ringing?	Yes	No
12	Do you get confused about where sounds come from?	Yes	No
13	Does your hearing suddenly worsen? In 24Hr.	Yes	No
14	Do you seem to hear out of on ear better than the other?	Yes	No

Appendix 2 Results of experiment

Appendix 2.1 The SAV results for experiment 3.1

	All-average	GNS-Group1	GNS-Group2	Male	Female
LFN1-PN-250-500Hz-15dB	4.64	3.75	5	5	4.44
LFN1-PN-250-1KHz-15dB	4.21	4.25	4.2	4.4	4.11
LFN1-PN-250-2KHz-15dB	4.57	4.25	4.7	4.8	4.44
LFN1-PN-250-4KHz-15dB	4.93	4.25	5.2	5	4.89
LFN1-PN-500-1KHz-15dB	4.57	4.75	4.5	4.6	4.56
LFN1-PN-500-2KHz-15dB	3.57	3.5	3.6	3.8	3.44
LFN1-PN-1K-2KHz-15dB	4.36	4.25	4.4	4.8	4.11
LFN1-PN-2K-4KHz-15dB	4.79	4.75	4.8	4.8	4.78
LFN1-PN-4K-8KHz-15dB	4.71	4.5	4.8	5	4.56
LFN1-PN-250-500Hz-20dB	4.29	4	4.4	4.4	4.22
LFN1-PN-250-1KHz-20dB	4.43	3.75	4.7	4.8	4.22
LFN1-PN-250-2KHz-20dB	4.14	3.75	4.3	4.6	3.89
LFN1-PN-250-4KHz-20dB	4.14	3.75	4.3	4.8	3.78
LFN1-PN-500-1KHz-20dB	4.43	4.5	4.4	4.4	4.44
LFN1-PN-500-2KHz-20dB	4.57	4.5	4.6	4.2	4.78
LFN1-PN-1K-2KHz-20dB	4.50	4.25	4.6	4.2	4.67
LFN1-PN-2K-4KHz-20dB	4.43	4	4.6	4.8	4.22
LFN1-PN-4K-8KHz-20dB	4.57	4.5	4.6	5.2	4.22
LFN1-PN-250-500Hz-25dB	3.71	3.5	3.8	3.6	3.78
LFN1-PN-250-1KHz-25dB	3.93	4.25	3.8	4.2	3.78
LFN1-PN-250-2KHz-25dB	4.21	4.5	4.1	4.8	3.89
LFN1-PN-250-4KHz-25dB	4.79	4.75	4.8	5.4	4.44
LFN1-PN-500-1KHz-25dB	5.00	4.5	5.2	5.4	4.78
LFN1-PN-500-2KHz-25dB	4.00	4	4	5	3.44
LFN1-PN-1K-2KHz-25dB	4.79	4.5	4.9	5	4.67
LFN1-PN-2K-4KHz-25dB	3.93	3.25	4.2	4.8	3.44
LFN1-PN-4K-8KHz-25dB	4.43	4.25	4.5	5.4	3.89
LFN1-WN-250-500Hz-15dB	4.31	4.75	4.17	4.2	4.36
LFN1-WN-250-1KHz-15dB	4.00	4.5	3.83	4.2	3.91
LFN1-WN-250-2KHz-15dB	4.75	5.25	4.58	4.4	4.91
LFN1-WN-250-4KHz-15dB	4.50	4.5	4.50	4.4	4.55
LFN1-WN-500-1KHz-15dB	4.44	4.25	4.50	4	4.64
LFN1-WN-500-2KHz-15dB	4.38	4.25	4.42	4.4	4.36
LFN1-WN-1K-2KHz-15dB	4.25	4	4.33	4.2	4.27
LFN1-WN-2K-4KHz-15dB	4.19	4.25	4.17	4.2	4.18
LFN1-WN-4K-8KHz-15dB	4.50	5.25	4.25	4.8	4.36
LFN1-WN-250-500Hz-20dB	4.38	4	4.50	4.2	4.45
LFN1-WN-250-1KHz-20dB	4.50	4.5	4.50	4.2	4.64
LFN1-WN-250-2KHz-20dB	4.06	4.75	3.83	4.4	3.91
LFN1-WN-250-4KHz-20dB	4.38	4.25	4.42	4.2	4.45
LFN1-WN-500-1KHz-20dB	4.50	5	4.33	4.2	4.64
LFN1-WN-500-2KHz-20dB	4.44	4.75	4.33	4.2	4.55

	All-average	GNS-Group1	GNS-Group2	Male	Female
LFN1-WN-1K-2KHz-20dB	4.56	4.75	4.50	5	4.36
LFN1-WN-2K-4KHz-20dB	4.75	5	4.67	4.6	4.82
LFN1-WN-4K-8KHz-20dB	4.44	4.5	4.42	5.2	4.09
LFN1-WN-250-500Hz-25dB	4.25	4.75	4.08	4.8	4.00
LFN1-WN-250-1KHz-25dB	4.27	5.25	3.91	4.2	4.30
LFN1-WN-250-2KHz-25dB	4.81	5.5	4.58	5	4.73
LFN1-WN-250-4KHz-25dB	4.25	4.5	4.17	4.2	4.27
LFN1-WN-500-1KHz-25dB	4.88	5.25	4.75	4	5.27
LFN1-WN-500-2KHz-25dB	4.44	4.5	4.42	4.8	4.27
LFN1-WN-1K-2KHz-25dB	4.44	5	4.25	4.4	4.45
LFN1-WN-2K-4KHz-25dB	4.69	4.75	4.67	4.6	4.73
LFN1-WN-4K-8KHz-25dB	5.38	6.25	5.08	5.6	5.27

	All-average	GNS-Group1	GNS-Group2	Male	Female
LFN2-PN-250-500Hz-15dB	4.67	4.50	4.75	5.00	4.56
LFN2-PN-250-1KHz-15dB	4.50	4.25	4.63	4.67	4.44
LFN2-PN-250-2KHz-15dB	4.75	4.50	4.88	5.00	4.67
LFN2-PN-250-4KHz-15dB	5.08	4.75	5.25	6.00	4.78
LFN2-PN-500-1KHz-15dB	4.75	4.25	5.00	6.33	4.22
LFN2-PN-500-2KHz-15dB	5.00	4.50	5.25	6.33	4.56
LFN2-PN-1K-2KHz-15dB	4.00	4.00	4.00	5.00	3.67
LFN2-PN-2K-4KHz-15dB	4.58	4.50	4.63	5.33	4.33
LFN2-PN-4K-8KHz-15dB	4.50	4.50	4.50	5.67	4.11
LFN2-PN-250-500Hz-20dB	5.00	4.50	5.25	6.33	4.56
LFN2-PN-250-1KHz-20dB	3.67	3.75	3.63	4.00	3.56
LFN2-PN-250-2KHz-20dB	3.83	3.75	3.88	4.00	3.78
LFN2-PN-250-4KHz-20dB	4.00	4.00	4.00	4.67	3.78
LFN2-PN-500-1KHz-20dB	4.75	4.50	4.88	4.67	4.78
LFN2-PN-500-2KHz-20dB	4.42	3.75	4.75	5.33	4.11
LFN2-PN-1K-2KHz-20dB	4.08	4.25	4.00	4.33	4.00
LFN2-PN-2K-4KHz-20dB	4.33	3.75	4.63	5.33	4.00
LFN2-PN-4K-8KHz-20dB	4.17	4.00	4.25	5.00	3.89
LFN2-PN-250-500Hz-25dB	4.25	4.00	4.38	4.33	4.22
LFN2-PN-250-1KHz-25dB	4.58	4.25	4.75	5.33	4.33
LFN2-PN-250-2KHz-25dB	4.83	4.75	4.88	4.67	4.89
LFN2-PN-250-4KHz-25dB	5.33	5.00	5.50	6.33	5.00
LFN2-PN-500-1KHz-25dB	4.08	4.00	4.13	5.00	3.78
LFN2-PN-500-2KHz-25dB	4.92	4.75	5.00	5.67	4.67
LFN2-PN-1K-2KHz-25dB	4.50	4.25	4.63	5.67	4.11
LFN2-PN-2K-4KHz-25dB	5.25	4.75	5.50	7.00	4.67
LFN2-PN-4K-8KHz-25dB	5.42	5.00	5.63	6.00	5.22

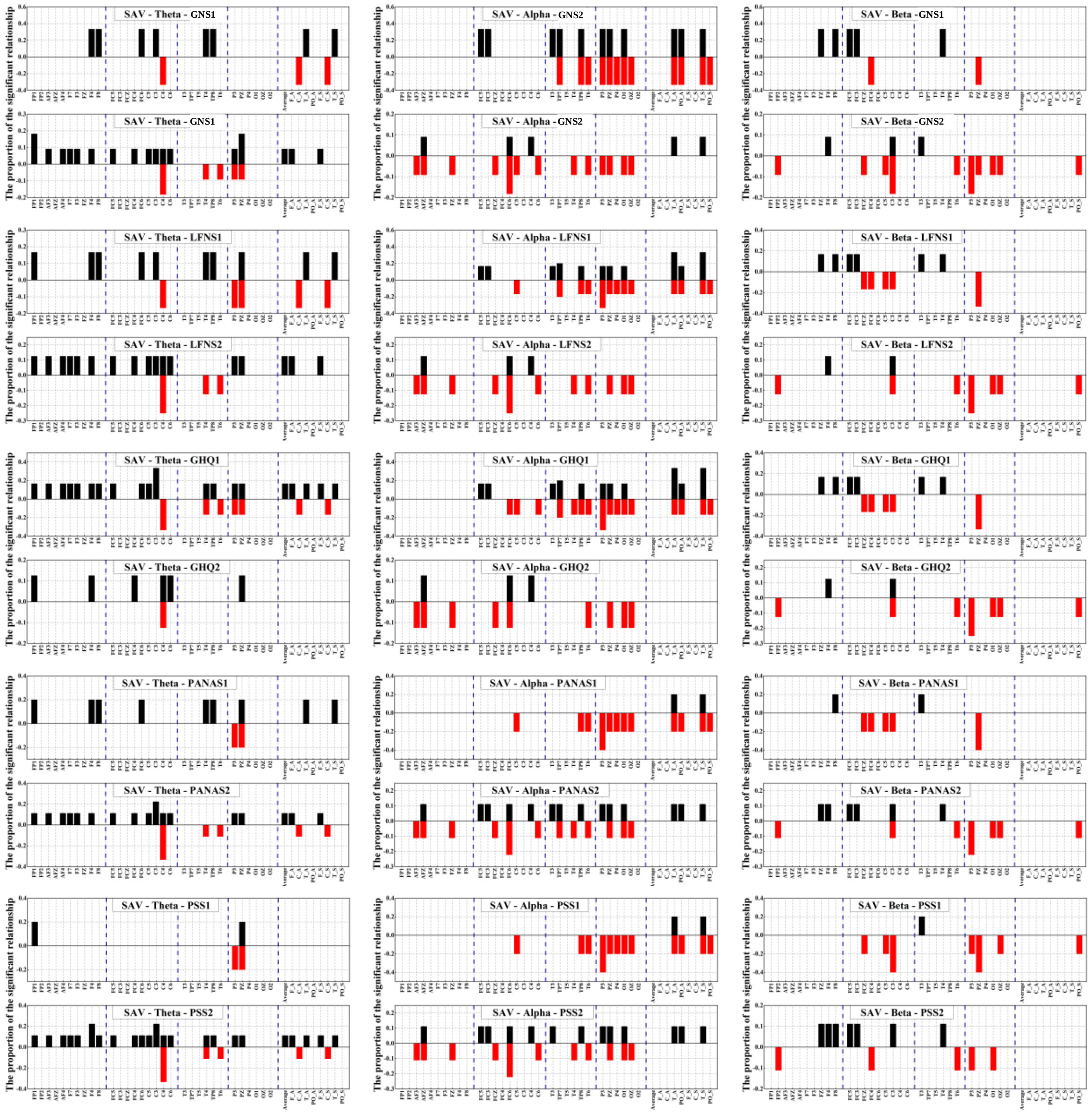
	All-average	GNS-Group1	GNS-Group2	Male	Female
LFN3-PN-250-500Hz-15dB	4.23	4.00	4.30	4.00	4.36
LFN3-PN-250-1KHz-15dB	4.31	4.00	4.40	3.75	4.45
LFN3-PN-250-2KHz-15dB	4.92	4.33	5.10	5.00	5.00
LFN3-PN-250-4KHz-15dB	4.92	4.33	5.10	5.25	4.82
LFN3-PN-500-1KHz-15dB	4.31	3.67	4.50	4.25	4.36
LFN3-PN-500-2KHz-15dB	4.69	4.00	4.90	4.75	4.73
LFN3-PN-1K-2KHz-15dB	4.46	4.00	4.60	4.25	4.45
LFN3-PN-2K-4KHz-15dB	4.46	4.00	4.60	4.25	4.64
LFN3-PN-4K-8KHz-15dB	4.77	4.33	4.90	5.00	4.82
LFN3-PN-250-500Hz-20dB	4.77	4.00	5.00	4.50	4.82
LFN3-PN-250-1KHz-20dB	4.69	4.33	4.80	5.00	4.73
LFN3-PN-250-2KHz-20dB	4.31	4.00	4.40	4.00	4.45
LFN3-PN-250-4KHz-20dB	4.38	3.67	4.60	4.50	4.45
LFN3-PN-500-1KHz-20dB	4.54	4.00	4.70	4.50	4.55
LFN3-PN-500-2KHz-20dB	4.31	4.00	4.40	4.00	4.36
LFN3-PN-1K-2KHz-20dB	4.62	4.67	4.60	4.25	4.73
LFN3-PN-2K-4KHz-20dB	4.46	4.00	4.60	4.25	4.55
LFN3-PN-4K-8KHz-20dB	4.46	4.00	4.60	4.75	4.45
LFN3-PN-250-500Hz-25dB	4.08	4.33	4.00	3.75	4.27
LFN3-PN-250-1KHz-25dB	4.38	3.67	4.60	4.25	4.55
LFN3-PN-250-2KHz-25dB	4.69	4.33	4.80	4.75	4.73
LFN3-PN-250-4KHz-25dB	4.69	4.67	4.70	4.25	4.82
LFN3-PN-500-1KHz-25dB	4.85	4.67	4.90	4.75	4.91
LFN3-PN-500-2KHz-25dB	4.62	4.67	4.60	4.00	4.73
LFN3-PN-1K-2KHz-25dB	5.00	5.00	5.00	4.75	5.18
LFN3-PN-2K-4KHz-25dB	4.69	4.67	4.70	4.75	4.64
LFN3-PN-4K-8KHz-25dB	5.08	5.00	5.10	4.75	5.09

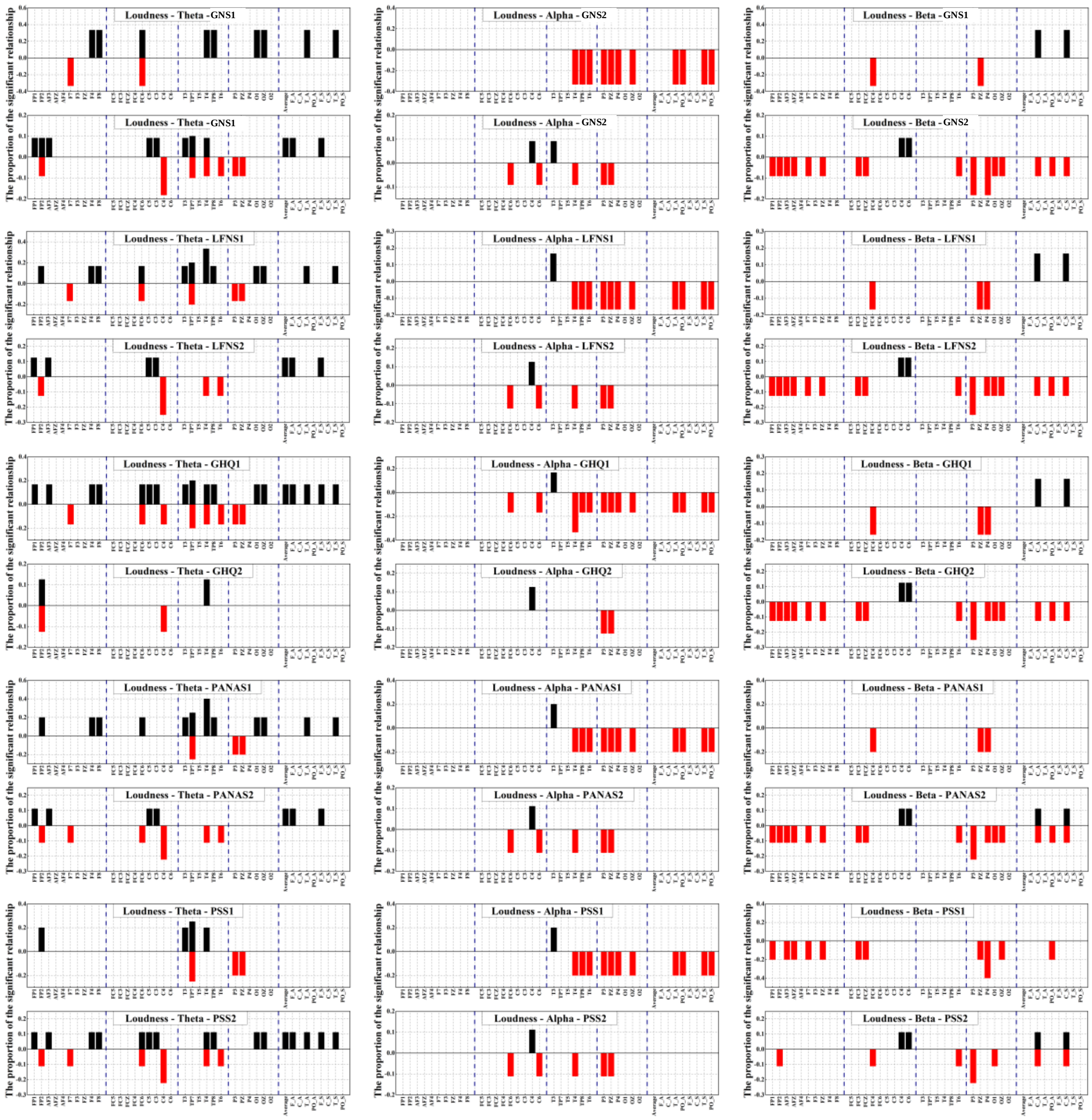
	All-average	GNS-Group1	GNS-Group2	Male	Female
LFN4-PN-250-500Hz-15dB	4.21	4.33	4.18	4.11	4.40
LFN4-PN-250-1KHz-15dB	4.57	4.67	4.55	4.67	4.40
LFN4-PN-250-2KHz-15dB	4.57	4.67	4.55	4.44	4.80
LFN4-PN-250-4KHz-15dB	4.14	4.00	4.18	4.11	4.20
LFN4-PN-500-1KHz-15dB	4.50	4.67	4.45	4.56	4.40
LFN4-PN-500-2KHz-15dB	4.21	4.33	4.18	4.33	4.00
LFN4-PN-1K-2KHz-15dB	4.07	4.00	4.09	4.11	4.00
LFN4-PN-2K-4KHz-15dB	4.29	4.00	4.36	4.44	4.00
LFN4-PN-4K-8KHz-15dB	4.50	4.33	4.55	4.33	4.80
LFN4-PN-250-500Hz-20dB	4.64	4.67	4.64	4.67	4.60
LFN4-PN-250-1KHz-20dB	4.50	4.67	4.45	4.56	4.40
LFN4-PN-250-2KHz-20dB	4.50	4.33	4.55	4.44	4.60
LFN4-PN-250-4KHz-20dB	4.50	5.00	4.36	4.56	4.40
LFN4-PN-500-1KHz-20dB	4.29	4.33	4.27	4.33	4.20
LFN4-PN-500-2KHz-20dB	4.14	4.00	4.18	3.89	4.60

	All-average	GNS-Group1	GNS-Group2	Male	Female
LFN4-PN-1K-2KHz-20dB	4.14	4.33	4.09	4.22	4.00
LFN4-PN-2K-4KHz-20dB	3.93	4.33	3.82	4.00	3.80
LFN4-PN-4K-8KHz-20dB	4.21	3.67	4.36	4.00	4.60
LFN4-PN-250-500Hz-25dB	4.00	4.33	3.91	4.00	4.00
LFN4-PN-250-1KHz-25dB	4.43	4.67	4.36	4.22	4.80
LFN4-PN-250-2KHz-25dB	4.36	4.33	4.36	4.44	4.20
LFN4-PN-250-4KHz-25dB	4.14	3.67	4.27	4.11	4.20
LFN4-PN-500-1KHz-25dB	4.36	4.00	4.45	4.22	4.60
LFN4-PN-500-2KHz-25dB	4.57	4.67	4.55	4.44	4.80
LFN4-PN-1K-2KHz-25dB	4.14	3.67	4.27	4.11	4.20
LFN4-PN-2K-4KHz-25dB	4.50	4.33	4.55	4.22	5.00
LFN4-PN-4K-8KHz-25dB	4.86	5.00	4.82	4.78	5.00
LFN4-WN-250-500Hz-15dB	4.20	5.00	3.91	4.10	4.4
LFN4-WN-250-1KHz-15dB	4.13	4.50	4.00	4.20	4
LFN4-WN-250-2KHz-15dB	4.47	4.75	4.36	4.60	4.2
LFN4-WN-250-4KHz-15dB	4.47	5.00	4.27	4.60	4.2
LFN4-WN-500-1KHz-15dB	4.47	5.00	4.27	4.70	4
LFN4-WN-500-2KHz-15dB	4.73	4.75	4.73	4.80	4.6
LFN4-WN-1K-2KHz-15dB	4.40	4.50	4.36	4.40	4.4
LFN4-WN-2K-4KHz-15dB	4.53	4.50	4.55	4.50	4.6
LFN4-WN-4K-8KHz-15dB	4.40	4.50	4.36	4.30	4.6
LFN4-WN-250-500Hz-20dB	4.20	4.50	4.09	4.20	4.2
LFN4-WN-250-1KHz-20dB	3.93	4.00	3.91	3.80	4.2
LFN4-WN-250-2KHz-20dB	3.80	4.00	3.73	3.90	3.6
LFN4-WN-250-4KHz-20dB	3.87	4.00	3.82	3.80	4
LFN4-WN-500-1KHz-20dB	3.93	4.75	3.64	4.20	3.4
LFN4-WN-500-2KHz-20dB	4.40	4.50	4.36	4.50	4.2
LFN4-WN-1K-2KHz-20dB	4.27	4.50	4.18	4.20	4.4
LFN4-WN-2K-4KHz-20dB	4.67	4.75	4.64	4.60	4.8
LFN4-WN-4K-8KHz-20dB	4.07	4.00	4.09	3.90	4.4
LFN4-WN-250-500Hz-25dB	4.00	4.25	3.91	4.10	3.8
LFN4-WN-250-1KHz-25dB	4.67	4.50	4.73	4.50	5
LFN4-WN-250-2KHz-25dB	4.60	5.25	4.36	4.80	4.2
LFN4-WN-250-4KHz-25dB	4.40	4.75	4.27	4.60	4
LFN4-WN-500-1KHz-25dB	4.53	4.25	4.64	4.50	4.6
LFN4-WN-500-2KHz-25dB	4.20	4.50	4.09	4.30	4
LFN4-WN-1K-2KHz-25dB	4.53	4.75	4.45	4.50	4.6
LFN4-WN-2K-4KHz-25dB	4.53	4.75	4.45	4.60	4.4
LFN4-WN-4K-8KHz-25dB	4.87	5.25	4.73	4.90	4.8

Appendix 2.2 The comparison results for the correlation of RPSD with SAV and loudness in experiment 3.4

(X axis - the same EEG electrode position as in Figure 3.4.18; Y axis - the proportion of the significant relationship with SAV or loudness)




The proportion of the significant relationship
Loudness - Theta -GNS1
Loudness - Alpha - GNS2
Loudness - Beta - GNS1
Loudness - Theta - GNS1
Loudness - Alpha - GNS2
Loudness - Beta - GNS2
Loudness - Theta - LFNS1
Loudness - Alpha - LFNS1
Loudness - Beta - LFNS1
Loudness - Theta - LFNS2
Loudness - Alpha - LFNS2
Loudness - Beta - LFNS2
Loudness - Theta - GHQ1
Loudness - Alpha - GHQ1
Loudness - Beta - GHQ1
Loudness - Theta - GHQ2
Loudness - Alpha - GHQ2
Loudness - Beta - GHQ2
Loudness - Theta - PANAS1
Loudness - Alpha - PANAS1
Loudness - Beta - PANAS1
Loudness - Theta - PANAS2
Loudness - Alpha - PANAS2
Loudness - Beta - PANAS2
Loudness - Theta - PSS1
Loudness - Alpha - PSS1
Loudness - Beta - PSS1
Loudness - Theta - PSS2
Loudness - Alpha - PSS2
Loudness - Beta - PSS2

List of Tables

List of Figures

Publications published by this Author

1. Mu He, Detlef Krahé, “EEG reaction under low frequency noise exposure”, the 22nd International Congress on Sound and Vibration (ICSV22), July 12 - 16, 2015, Florence, Italy.
2. Mu He, André Leickel, Detlef Krahé, “*The visual effect combined with audible noise of wind turbine and its related EEG reaction*”, the 10th European Congress and Exposition on Noise Control Engineering, May 31 - June 3, 2015, Maastricht, Holland.
3. Mu He, Zhiyong Deng, Detlef Krahé, “*The EEG variation caused by the LFN*”, 11th International Congress on Noise as a Public Health Problem (ICBEN), June 1 - 5, 2014, Nara, JAPAN.
4. Mu He, Zhiyong Deng, Detlef Krahé, “*The subjective influence of LFN combined with pink and white noise*”, The 40th Annual German Congress on Acoustics (DAGA), Mar. 10 - 13, 2014, Oldenburg, Germany.