

# Neural Correlates of Noise Annoyance and Sensitivity



Jenny S.Y. Lee<sup>1</sup>, Michael J. Hautus<sup>1</sup> and Daniel Shepherd<sup>2</sup>

<sup>1</sup>Department of Psychology, The University of Auckland, New Zealand

<sup>2</sup>Department of Psychology, Auckland University of Technology, New Zealand

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## Abstract

The relationship between noise and affective response is not well understood, and there have been calls for further physiological investigation. To investigate subjective responses to noise, an attempt is made here to analyze the auto-correlation function of alpha activity during the presentation of annoying sounds. Twelve real-world sounds (e.g. baby's cry, snoring) were presented to a small sample ( $n = 16$ ), who listened while having their scalp potentials recorded. Noise sensitivity questionnaires were used to assess participants' sensitivity to noise in general. Findings indicate that those who are noise sensitive appear easily aroused by noise regardless of the magnitude of annoyance. In contrast, participants who classified as noise resistant are typically aroused only when the most annoying sounds are presented. These results suggest a difference in processing between the noise sensitive and the noise resistant individuals. The current investigation may provide a basis for future studies to evaluate the underlying neural processes associated with noise annoyance.

## INTRODUCTION

At the psychological level of description, noise can be broadly defined as unwanted and intrusive sounds that one would prefer not to hear [1]. Noise interferes with daily activities and these disturbances often elicit feelings of annoyance or irritations in the listener [2]. People who are extremely annoyed by noise may experience maladaptive, negative emotions such as anger or fear towards the source of noise [3]. These emotions are usually accompanied by physiological arousal, which could further reinforce the initial affective reactions. Noise annoyance describes a multifaceted response that covers both affective dimensions and the immediate behavioural effect of noise [4].

An increasing body of literature supporting the role of noise sensitivity in noise perception is emerging [5].

Noise sensitivity is defined as a mediating factor between noise-induced annoyance and noise exposure [6]. Weinstein [7] postulated that noise sensitivity could be understood as a general tendency of the individual to express negative judgments of their immediate environment. Stansfeld [1] further refined this definition to consider noise sensitivity as a stable personality trait composed of two key characteristics. First, noise sensitive individuals have a predisposition to attend to sounds and to perceive them negatively. Second, these individuals display stronger emotional reactions to noise [1].

Unfortunately, most investigations into noise impacts mainly focus on annoyance generated by noise from transport infrastructures and industrial complexes. Comparatively, other noises such as the rustling of papers, snoring or a baby's cry have often been neglected [8]. To date, the effects of these everyday sounds remained inconclusive. Accordingly, a broader approach

in measuring noise annoyance is needed.

In the past decade, a neural-based model has been developed by Ando [9] to assess subjective preferences for sounds. According to this model, subjective preference is mirrored in changes in alpha activity when exposed to noise [10]. This model takes advantage of the physical properties of sound waves to calculate how the brain processes acoustic information at each stage of the auditory system.

Numerous studies by Ando [10] calculated the persistence of alpha activity in the electroencephalogram (EEG) using autocorrelation functions (ACF). The ACF is a procedure for identifying the similarity within a monaural signal as a function of time-lag [11]; that is to find repeating patterns within the signal itself across time. Therefore, the continuity of alpha activity describes how self-similar the signal is within a set period of time.

Interestingly, it has been found that the effective duration of temporal and spatial factors of sounds are processed differently in the brain. The effective duration is the time over which the sound is acoustically self-similar and less degraded by other factors before it enters the ears [10]. Hence, this represents the short period of time where the properties of sounds remain the same.

A study by Mouri, Akiyama and Ando [12] found a correlation between the effective duration of sounds and that of alpha wave activity with different subjective preferences. Participants were asked to listen to 10 seconds of music inside an anechoic chamber while having electrical activity recorded from their scalps [10]. Both the neural activity and the sound stimuli were analysed using the ACF. The effective duration of alpha waves in the left hemisphere persistently correlated with the effective

duration of (and thus preference for) the 10 second piece of music [12]. This investigation revealed two important pieces of information regarding the auditory-brain model. First, the persistence of alpha waves suggests a preference for that sound stimulus. [12]. Second, greater alpha waves were found in the left hemisphere compared to the right suggesting that the left hemisphere is more responsive to positive evaluations of sounds.

Another study by Soeta, Nakagawa, Tonoike and Ando [13] explored different patterns of neural activity in participants listening to different sounds. The sound stimuli included pure tones or bandpass noises with a centre frequency of 1000 Hz. Participants were required to listen to these sounds via an earpiece within an anechoic chamber [13]. Results revealed that alpha activity was detected in the left hemisphere during pure tone conditions [13]. However, during the presentation of bandpass noise, the effective duration of the alpha rhythm decreased dramatically. These findings were consistent across participants in the study suggesting that annoyance could be a function of the persistence of brain oscillations.

The primary intention of the present investigation was to develop a quantitative procedure to guide future studies in the assessment of noise annoyance. Specifically, to quantify the qualitative aspects of noise annoyance by comparing the corresponding changes in alpha persistence when annoying stimuli were presented. Furthermore, these changes will also be compared against the listeners' level of noise sensitivity. The aforementioned studies of the auditory-brain model suggested that subjective preference for a sound could be recognized from the increase of alpha persistence. Consequently, it is postulated that alpha persistence would decrease when annoying acoustic stimuli are presented irrespective of the level of sensitivity.

## MATERIALS AND METHODS

### Participants

The present study consisted of 17 participants (7 male), aged between 18 and 28 years (mean age = 22.37 years). Data from one participant was discarded prior to analysis due to inattention during the session. Participants were categorised into two groups; noise sensitive and noise resistant, based on their scores from the Noise Sensitivity Questionnaire (NOISEQ). Each group consisted of eight participants. None of the participants reported any forms of hearing impairment or a medical history of neurological disease. Ethics approval was obtained prior to the commencement of the study, as well as informed consent from each participant.

### Stimuli and apparatus

#### Acoustic stimuli

A total of 12 digitized emotional sounds taken from the International Affective Digitized Sounds (IADS) library were used [14]. The duration of each sound was six seconds. The 12 stimuli were selected based on their mean valence and arousal scores as reported by Redondo, Fraga, Padron and Pineiro [15]. Stimuli were presented using LabView (TM) software (National Instrument; NI). The level of the stimuli was adjusted using programmable attenuators (Tucker-Davis Technologies; TDT), to yield 70dB SPL at the earphone. The stimuli were then routed through a headphone driver (TDT HB7) and presented

via inserted earphones (Etymotic ER2).

### Electroencephalogram (EEG)

All EEG recordings were conducted in a modular shielded room using 128-channel Ag/AgCl electrode nets (Electrical Geodesics Inc.), according to the 10/20 international system of electrode placement. All EEG signals were recorded continuously at a sampling rate of 250 Hz (0.1-100 Hz analogue bandpass) with Electrical Geodesics Inc. amplifiers (200 M $\Omega$  input impedance). Electrode impedances were kept below 40 k $\Omega$ . All EEG signals were acquired using a common vertex (Cz) reference and were processed by Net Station (Version 4.2) on an 8-core Apple Mac Pro workstation.

Each session was divided into two blocks. A total of 12 different sound stimuli were presented to the listener: each stimulus was repeated 7 times in each block. Thus a total of 168 sounds (12 x14) were presented to the listener in one experimental session. The order of stimuli presentation was randomized and the interstimulus (offset to onset) interval was 6000 ms.

### Noise sensitivity questionnaire (NOISEQ)

Each participant's level of noise sensitivity was estimated using the Noise Sensitivity Questionnaire (NOISEQ), which was adopted from the Weinstein Sensitivity Scale. The scale consists of 35 items which when averaged provide a measure for global noise sensitivity, as-well-as sensitivity in five everyday life domains (leisure, work, habituation, communication and sleep). Each item asks the participant to identify their level of agreement regarding noise-related statements on a five point Likert-type scale. Global noise sensitive scores were computed as the mean of 35 items on the scale. Low scores indicate greater sensitivity whereas higher scores represent greater resistance to noise.

### Annoyance ratings

The degree of perceived annoyance for each sound stimulus was recorded on a computer immediately after each stimulus was presented. During the annoyance rating section, the same 12 sound stimuli were presented consecutively to the listener in an anechoic chamber. After the presentation of each sound stimulus, participants were asked to rate, on a scale of 1 (least annoying) to 5 (most annoying), the degree to which the sounds were annoying. The presentation order of stimuli was randomized.

### Procedure

The study was conducted within a laboratory setting, including the completion of the Noise Sensitivity Questionnaire prior to the experiment.

The experiment was divided into two parts: EEG recordings and annoyance ratings. The EEG section was divided into two blocks and participants were given a short break (5-10 minutes) between them. During each block, participants sat 57 cm in front of a computer monitor in a modular shielded room and listen to sounds. Participants were instructed to sit still and listen to the sounds passively while having their scalp activity measured. Neutral pictures, such as tables and chairs, were shown on the monitor as the sound stimuli were presented. Each block was approximately 15 minutes in duration.

After the EEG recordings, participants were seated comfortably

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in an anechoic chamber while they rated the degree of annoyance for each sound stimulus. The same series of sounds were presented in random order. Each participant was instructed to attend passively to the sounds and imagine hearing those sounds when they were concentrating on a task. The entire annoyance rating procedure was approximately 20 minutes. All experimental procedures were completed individually, and no incentives were offered.

### Data analysis

All statistical analyses, parametric, non-parametric, and autocorrelation, were conducted using the Statistical Package for Social Science (SPSS) version 17.

### EEG analyses

After completion of data collection, EEG raw files were filtered with a Butterworth band-pass filter (alpha; 8Hz-12Hz) and segmented, according to event markers, into 6000-ms epochs, including a 100-ms pre-stimulus baseline. Ocular artefacts were removed, and trials in which any of the electrocogram channels were marked as non-responsive were discarded prior to the averaging process. The voltages measured from these electrodes were averaged in their respective sound stimuli condition and a grand average was calculated for each members of the noise sensitive and the noise resistant group. The autocorrelation functions for all grand averages were computed, and the average autocorrelation from time zero were calculated according to level of sensitivity and 600-ms pre- and post-stimulus onset.

### Noise sensitivity questionnaires and annoyance ratings

Prior to computing the noise sensitivity scores, any negatively-worded items were recorded, and means and standard deviations calculated and inspected for evidence of floor or ceiling effects.

Participants were divided into groups of noise sensitive and noise resistant according to the median score. Participants' annoyance ratings were computed and a total value of annoyance was calculated for each sound stimulus. Sound stimuli were ranked from most annoying (highest ratings) to least annoying (lowest ratings) for both the noise sensitive and noise resistant participants. Thus, in this way, the 6 most annoying and the 6 least annoying sound stimuli were identified.

## RESULTS

### Study Population Characteristics

Independent-samples t-tests were conducted to compare the noise sensitivity scores and age between the noise sensitive and the noise resistant participants (see Table 1).

**Table 1. Descriptive data for the study population. Results were presented in means (s.d).**

	Noise sensitive (n=8)	Noise resistant (n=8)	Study total (n=16)
Age	23.00 (2.32)	21.75 (3.45)	22.37 (2.92)
Noise sensitivity scores	2.55 (0.22)	3.22 (0.32)	2.88 (0.44)

**Table 2. Ratings for each sound stimulus in descending order of annoyance for the noise sensitive and the noise resistant individuals.**

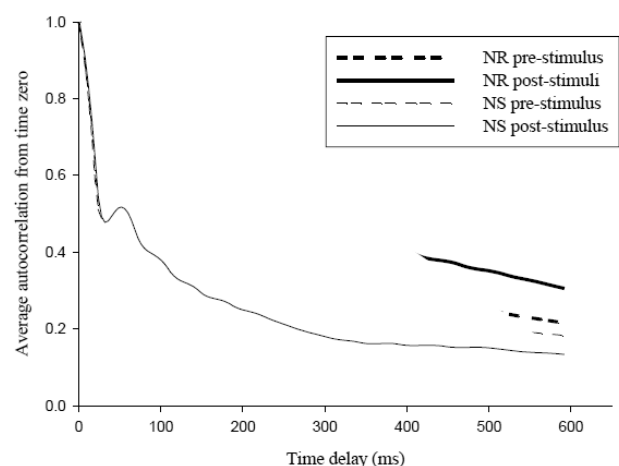
Degree of annoyance	Noise sensitive	Noise resistant
Most annoying	Mosquito	Baby crying
	Snoring	Snoring
	Baby crying	Mosquito
	Lawnmower	Chewing
	Chewing	Lawnmower
	Radio tuning	Radio tuning
	Whistling	Jet take-off
	Seagull	Toilet flushing
	People laughing	Whistling
	Dog barking	People laughing
	Toilet flushing	Dog barking
Least annoying	Jet take-off	Seagull

There was a significant difference in sensitivity scores between both groups ( $t(14) = -4.88, p < .001$ ). However, the effects of age did not reach statistical significance. Furthermore, chi-square tests (Yates Continuity Correlation) indicated no significant association between gender and level of sensitivity ( $X^2(1, n = 16) = 2.4, p = .12, \phi = -0.52$ ).

### Annoyance Ratings

The annoyance ratings for all sound stimuli were computed and ranked from the highest score (most annoying) to the lowest score (least annoying) for both groups. As shown on Table 2, the most and least annoying sound stimuli were the same for both the noise sensitive and the noise resistant participants.

### Autocorrelation Functions of Alpha Persistence



**Figure 1. Alpha persistence for the pre- and poststimulus onset between the noise sensitive (NS) and noise the resistant (NR) participants.**

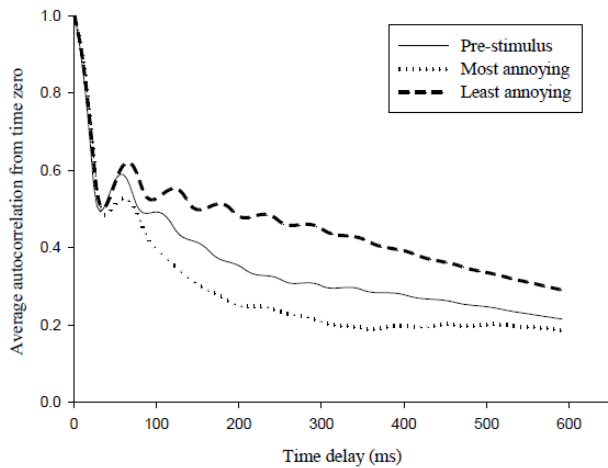


Figure 2. Alpha persistence for pre-stimulus, the most and the least annoying post-stimulus conditions for the noise resistant participant.

### Pre- and Post-stimulus Onset

Overall, there were marked changes in alpha persistence after the stimuli were presented. In particular, presentation of the stimuli led to an increase in alpha persistence for the noise resistant participants as shown in Figure 1. In contrast, a decrease in alpha persistence was observed upon the presentation of the stimuli for the noise sensitive participants.

Close inspection revealed a dramatic difference in alpha persistence among levels of annoyance between members of the noise sensitive and the noise resistant group. As shown in Figure 2, compared to the persistence prior to stimulus presentation, the most annoying stimuli resulted in a decrease in alpha persistence for the noise resistant participants. Conversely, the least annoying stimuli were found to increase the persistence in alpha activity in this group.

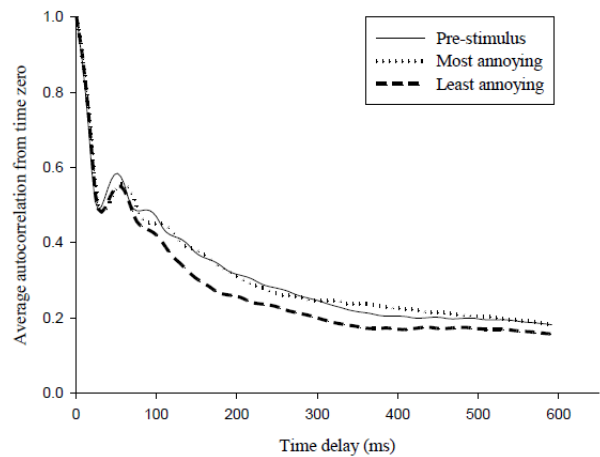


Figure 3. Alpha persistence for pre-stimulus, the most and the least annoying post-stimulus conditions for the noise sensitive participants.

Meanwhile, the changes in alpha persistence were less apparent for members of the noise sensitive group. As shown in Figure 3, compared to the alpha persistence before the onset of stimuli, the least annoying stimuli demonstrated a decrease in alpha persistence. Remarkably, the alpha persistence before and after the presentation of most annoying stimuli were relatively similar.

## DISCUSSION

In the current investigation, the subjective evaluation of noise between noise sensitive and the noise resistant individuals was examined. The primary intention of the present study was to ascertain whether changes in phased-locked alpha persistence could be used as an objective indicator for assessing noise annoyance.

Building from the work of Ando [10], the autocorrelation



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function was applied to analyse the duration of alpha activity when stimuli with differences in annoyance were presented. Accordingly, differences in the persistence of alpha activity between noise sensitive and noise resistant individuals could validate the effectiveness of using the autocorrelation function to assess the subjective evaluation of annoying sounds. To date, the precise physiological and functional role of alpha activity remains controversial. The classical understanding of alpha rhythms suggests that they are associated with a state of mental and physical relaxation [16].

High alpha oscillations are found during meditation and have shown to be inversely correlated with arousal level [17]. In contrast, low alpha oscillations are correlated with increased attention or other forms of mental processing [18]. These findings suggested that the individual with high alpha activity could be in a state of tranquillity and free of mental activity.

Moreover, existing research suggests that alpha rhythms represent a stand-by state of the brain [19]. To illustrate, the idle state of the brain could be thought of as similar to a computer that is merely turned on. As the lights on a computer could act as an indicator for its activation, alpha oscillations could also be a marker for this activated state. Some studies suggest that during this state, alpha oscillations have inhibitory control over other mental processing [20]. Thus decrease in alpha persistence would be an indicator for the activations of networks of neurons to carry out oriented functions [19].

The reduction in phase-locked alpha persistence demonstrated in the present study suggests that extremely annoying sounds can induce alpha desynchronization in both noise sensitive and noise resistant individuals (see Figure 2 and 3). These results are consistent with studies by Soeta et al [13] where a reduction of alpha activity was observed when bandpass noises are presented to participants.

A disruption in alpha oscillation suggests that the individual is no longer at a state of relaxation and other mental processing may be occurring [19]. This implication is rooted in numerous psychophysiological studies where diminished alpha rhythms have been observed during motor activation [21], attention processing [22], and sensory-semantic processing [23]. Therefore, it is plausible that a lowering of alpha persistence after the presentation of sounds is due to arousal and activation in mental functioning.

Speculatively, the increase of alpha persistence after the least annoying sounds are presented to the members of the noise resistant group (see Figure 2) may reflect the strengthening of the inhibitory function of the alpha rhythm. The aforementioned studies have illustrated that attention and other mental effort is reflected in a reduction in alpha activity, thus an increase in alpha rhythm will indicate a lack of mental processing in the cortex [17]. This proposes that the noise resistant participants in the present study may have the capacity to filter out noises that are judged as less annoying.

In addition, the least annoying sound results in a lower alpha persistence compared to the most annoying sounds for the noise sensitive participants (see Figure 3). Admittedly, this finding appears contradictory to what is discussed so far given that the most annoying sounds are expected to decrease alpha persistence. Yet it is possible that large variability between

members of the noise sensitive group may have led to this result.

To illustrate, participants in the present study were categorized into noise sensitive and noise resistant based on their total noise sensitivity score relative to the sample's median score. Thus it is reasonable to suspect that large individual differences among noise sensitive participants may have led to this mixed finding. Moreover, measures of noise sensitivity among participants were relatively low compared to field studies. For example, an extensive airport study by Shepherd, Welch, Dirks and Mathews [24] had a mean sensitivity score of 3.50. This value is greater compared to the mean sensitivity score of 2.88 found in the present study. Therefore, differences in the level of sensitivity may have contributed to the inconsistent results among noise sensitive participants. In short, the reduction of alpha persistence between the noise sensitive and the noise resistant participants may reflect arousal and activation of other mental processes.

Moreover, the generation of alpha activity in noise resistant participants when annoying sounds are presented suggests differences in processing. As the decrease of alpha persistence was only found when the most annoying sounds were presented, this implies an ability to differentiate between magnitudes of annoyance using electrophysiological indices.

## CONCLUSION

In the past decades, increases in community noises have been concerning the general population. As noises from transport infrastructures and industrial complexes becomes a daily nuisance, constant exposure becomes a psychological and physiological burden.

Past approaches to the assessment of noise annoyance relied on correlating levels of annoyance with acoustic and non-acoustic properties of noise. Among these non-acoustic parameters of noise, an individual's level of sensitivity to noise has been shown to influence self-reported annoyance. With the advanced neuroimaging technologies, a better understanding of individual differences in noise annoyance is possible.

In the present study, the persistence of alpha activity provides a promising approach to understand the qualitative aspects of noise annoyance. Compared to traditional methods, a description of noise annoyance is obtained by studying the durations of alpha activity among individuals with different levels of noise sensitivity. The differences in alpha persistence between the noise sensitive and the noise resistant participants provided information on how annoying sounds are perceived.

Specifically, the noise sensitive participants have a tendency to be aroused by noise easily. They also have difficulties in distinguishing noises that are different in magnitudes of annoyance. In contrast, being insensitive to noise is shown to have a buffer effect. It protects the noise resistant individuals from being distracted by noises that are judged as less annoying. However, as the precise functional role of alpha activity remains inconclusive, evidence from the present study may need to be interpreted with cautions. Irrespective, the current investigation provides supporting evidence suggesting that alpha persistence could be used to understand the subjective evaluation of sounds.

## IMPLICATIONS

With respect to the objectives of the present investigation, the findings revealed here show that the persistence of alpha activity, as shown by the autocorrelation function, may be an objective tool for assessing noise annoyance. This additional tool could add to the current understanding regarding sensitivity to noise from a neurological standpoint. Results from the current study confirm that the characteristics of noise sensitive participants may be rooted in physiology. For instance, a tendency to be aroused by noise is evident among noise sensitive participants. Moreover, the characteristics of noise resistant participants, such as the apparent protective effect against noise are evident in the present study. Taken together, findings from the current investigation reiterates how vital an objective measurement is for noise annoyance assessment.

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