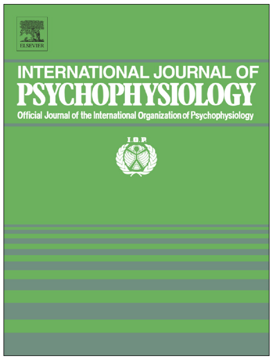

Electrophysiological indices of amplitude modulated sounds and sensitivity to noise

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Electrophysiological indices of amplitude modulated sounds and sensitivity to noise.

ABSTRACT

Annoyance to unwanted sound differs across individuals, though why noise sensitive individuals are more reactive to noise while others are more resilient remains unanswered. The Information Processing Hypothesis posits that noise sensitive individuals are vulnerable to higher-order auditory processing deficits. The aim of this study was to test the veracity of this hypothesis by documenting differences in pre-attentive auditory evoked potentials (ERP) between high noise sensitive and low noise sensitive individuals. Participants provided annoyance measures for three amplitude-modulated sounds, and were exposed to the sounds while undergoing electroencephalogram recording. Results indicated that annoyance increased with modulation, and that modulation affected both N1 and P2 components. At the group level, highly noise sensitive individuals exhibited significantly greater annoyance to a low-frequency tone, alongside significantly higher P2 amplitude, than individuals reporting low levels of noise sensitivity. Overall, the results partially supported the Information Processing Hypothesis of noise sensitivity, but also suggest that acoustic features may be more important than hitherto argued.

Keywords: Event-related potentials; Noise sensitivity; Amplitude modulation; Negative affectivity.

1. Introduction

As a generalisation, noise is an unwanted sound that typically conveys neither useful information nor hedonic value to the recipient. Noise sensitivity (NS) can be conceptualised as a persistent personality trait describing individuals who, during waking states, typically react negatively to ambient sound. In comparison, non-noise sensitive individuals are typically unaffected by ambient sound, though are also capable of negative reactions when unwanted sound directs attention and interferes with tasks or rest states. However, for non-noise sensitive individuals this ‘state’ noise sensitivity is usually contextual, transient, and not considered an enduring trait. In many clinical populations, for example schizophrenia, autistic spectrum disorder, anxiety, depression, and those with traumatic brain injuries, NS is a common symptom. Furthermore, individuals who are prone to noise-induced sleep disruption are likewise commonly labelled as noise sensitive (Dang-Vu et al., 2010), though there is no evidence to link the underlying sleep-related neurophysiological processes with those occurring in conscious individuals experiencing NS.

The psychological characteristics of noise sensitive individuals are best approached from two levels of description: affective and cognitive, though to a degree the relationship between the two is bi-directional. Affective (or emotional) responses have been discussed widely in the environmental noise-related literature under the guise of ‘annoyance’ responses. Noise sensitivity is a potent predictor of noise annoyance, which can range from states of mere irritation to the extremes of psychological distress and anger (Baudin et al., 2018). Adverse reactions to noise have been shown to coincide with sympathetic arousal (Panuvic, 2014), and are argued by some (Weinstein, 1980) but not others (Shepherd et al., 2016) to reflect negative affect, or a general tendency to complain. The so-called ‘negative affect’ Hypothesis of NS (Shepherd et al., 2015; Stansfeld, 1991) argues that NS is not linked to the physical characteristics of the sound (e.g., sound pressure level, spectral content, amplitude modulation), and that any audible sound has the potential to annoy an individual with NS.

Approaches using event-related measures extracted from the electroencephalogram (EEG) offer a means to assess the relative contribution of information processing deficits to NS. In the current context a primary measure of comparison would be auditory event-related potentials (ERP), which are scalp-recorded electrical signals reflecting the activity of (typically) pyramidal cells. As a times series, an ERP is characterised by voltage (V) deflections varying in amplitude (i.e., μV) and polarity (i.e., P: positive; N: negative), with an emphasis on the order or latency in which characteristic deflections occur to time locked acoustic events. As a generalisation, greater amplitude is indicative of greater neural activity occurring in the vicinity of the EEG sensor. For the early components of auditory ERPs considered in the current study, the first negative deflection (N1) represents neural processes involved with the extraction of sensory-related attributes from the sounds, while the second negative deflection (N2) is thought to involve higher order processing that classifies sounds (Pritchard Shappell, & Brandt, 1991). Finally, the second positive deflection (P2) depends on the acoustic features of the sound, for example sound intensity. The P2 has been implicated in the neural processes that direct attention to ambient stimuli (Luck & Hillyard, 1994).

At the cognitive level, NS is associated with impaired information-processing (Belojevic et al., 2003; Hughes et al., 2011), and in clinical populations impaired bottom-up attentional processes have been evoked to explain sensitivity to auditory distractors (e.g., Wright et al., 2014). There is little evidence to suggest that NS is related to the early processing of stimulus characteristics *per se*, and thus the amplitude of the N1 component should be equivalent across the spectrum of NS, as has been shown (Kliuchko et al., 2016). However, in the general population noise annoyance has been shown in part to be stimulus-oriented, for example, in a review Marquis-Favre, Premat and Aubr´ee (2005) report that amplitude modulated sound is more annoying and resistant to habituation than steady state sounds. Further, sounds with low-frequency components have been identified as potent catalysts of noise annoyance (Berglund, Hassmen, & Job, 1996). Because noise annoyance is known to impair cognitive function and interfere with goal-directed behaviour (Belojevic et al., 2003), possibly by impairing filtering processes that regulate cognitive load, it would be expected that beyond the early stimulus-related components of the ERP (i.e., the N1), differences between highly noise sensitive and non-noise sensitive individuals would be found. Furthermore, as stimulus features such as amplitude modulation and low-frequency tonal components are known to induce annoyance (Bradley, 1994), increasing these attributes may serve to decrease differences in the ERPs between highly noise sensitive and non-noise sensitive individuals, pertinently as the latter begin to exhibit annoyance.

Considering the clinical evidence from studies into schizophrenia, Shepherd et al. (2016) proposed that impaired pre-attentive information processing in the form of sensory gating deficits could explain noise sensitivity in non-clinical populations. Sensory gating is a neurological process by which redundant or irrelevant elements of the incoming stimulus field are filtered out. The degree of sensory gating is commonly indexed using the P50 paradigm, a positive deflection found in the ERP about 50 ms after a repeated click stimulus. The P50 is thought to reflect a filtering mechanism that impedes irrelevant sensory information and manages cognitive load (Gjini, Burroughs, & Boutros, 2011). Adopting the paired-clicked paradigm of White and Yee (2006), Shepherd et al. (2016) reported that differences in the P50 between a high and a low noise sensitive group were context dependent, noting significant differences between groups only when participants were engaged in an auditory attention task, but not a visual attention task nor during passive listening. For the auditory attention task, mean sensory gating was significantly lower in the highly noise sensitive group. Additionally, during the passive listening condition a significant decrease in P2s was found between the first and second click for those with high levels of NS sensitive but not those with lower levels. Some have argued that over-processing can lead to decreased P2 amplitude, indicating an increase in selective attention (Phillips & Takeda, 2009). In a study combining both EEG and MEG, Kliuchko *et al*. (2016) used a multifeature mismatched negativity paradigm to assess the integrity of auditory processing in low versus high noise sensitivity groups. They replicated the results of Shepherd et al. (2016) in finding impaired sensory gating in their high NS group, though their approach did not afford the analysis of later components associated with feature segregation such as the P2.

The information processing and negative affect approaches to NS constitute competing hypotheses, however, experimentally it is not easy to disentangle the two. Typically, studies have focused on one approach or the other, for example, seeking evidence for (or against) the Negative Affect Hypothesis (e.g., Persson et al., 2007). The current study endeavours to test the veracity of the Information Processing Hypothesis by adopting the forced-choice procedures described by Ando (2009) in order to partial out the effects of negative affect. Highly noise sensitive individuals exhibiting negative affect would be inclined to assess noise as uniformly annoying. By presenting pairs of noises and forcing participants to indicate which is the more annoying, Ando’s paired comparison test creates a hierarchy of annoyance in which the influence of negative affect should be negligible. In this scheme, reflexive critical tendencies are suppressed as highly noise sensitive individuals direct their focus to the stimulus characteristics driving their annoyance responses. Consequently, the variability in annoyance responses elicited by highly noise sensitive individuals can be maximised, and their ERPs directly compared across the hierarchy of annoyance. Note too that this approach also benefits the operationalisation of noise annoyance across those with no or low levels of NS, who may be inclined to be indifferent to noise and consistently rate different sounds as not annoying.

When comparing across high and low noise sensitive individuals it is acknowledged that members of both groups can become highly annoyed by noise, depending upon context. This is especially true during task engagement, with Pripfl et al. (2006) noting no differences in early EEG components (e.g., P2) between high and low noise sensitive individuals engaged in numerical tasks while exposed to noise. Additionally, Shepherd et al. (2016), employing the paired-clicked paradigm, found that the P2 amplitude was linked to NS only during passive listening conditions. Hence a better way to compare ERP components, such as the P2, across the two groups might be to avoid task-dependent experimental contexts and instead obtain measurements while the participants are in a state of passive listening. Furthermore, the use of a stimulus set that has been manipulated to be increasingly annoying should expose similarities and differences across the NS continuum. By manipulating stimulus properties, notably spectral characteristics (e.g., low-frequency tone, noise, piano tones) and amplitude modulation depth, annoyance responses to sound containing low frequencies and/or are heavily modulated should be independent of NS. However, as salient low-frequency components are removed and amplitude modulation depth lessens, reactivity and annoyance should be greater in those with higher-levels of NS. Because the Information Processing Hypothesis would argue that annoyance is linked directly to components of the auditory ERP, then these differences should likewise be detected in components such as the P2.

Currently there is little understanding of NS at the biological level of description, and more research has been called for (e.g., Dzhambov, 2015; Kliuchko *et al.*, 2016). The aim of the current study is to examine the effects of amplitude modulated sounds on behavioural (i.e., annoyance) and EEG measures while participants varying in NS listen passively. While NS is highly prevalent in many clinical populations experiencing psychopathology, the current study opted to recruit individuals without past or existing psychiatric conditions. The advantage of using participants without membership to a clinical group is that NS can be studied without the need to disentangle the effects of experimental variables from a myriad of clinical symptoms.

2. Methods

2.1 Participants

The present study comprised thirty participants (14 male), aged between 18 and 44 years (M_{age} = 24.77 years, *SD* = 5.47). None of the participants reported a history of hearing impairment, neurological disease, clinical diagnoses, or medication use. All experimental procedures were approved by the University of Auckland Human Participants Ethics Committee (2011/238), and informed consent was obtained from each participant at the beginning of the experiment. To ensure participants were near the extremes of the noise sensitivity scale, the noise sensitivity scores from a population study (Shepherd et al., 2010) were used as a reference (M_{NS} = 2.85, *SD* = 0.49). From this study, the range of sensitivities bracketing the top and bottom 15 percent of the data was used as a guideline for recruitment in the present study. Participants who fell within these pre-determined criteria were allocated to either the high NS (HNS) or low NS (LNS) group, with recruitment continuing until each group consisted of 15 participants. The mean age of LNS group was 24.20 years (*SD* = 3.09), and the HNS group 25.33 years (*SD* = 7.18).

2.2 Sound Stimuli

A total of 15 stimuli were created from three base sound files; one C major seventh piano chord (hereon ‘chord’), one burst of 100-Hz low-pass white noise (hereon ‘white noise’), and one 50-Hz low-frequency sine wave (hereon ‘tone’). The chord was retrieved from an online sound library, whereas the noise and tone were constructed in LabView v.8.5 (National Instruments, Texas, USA) using a sample rate of 44.1 kHz. Each of the three sounds was transformed according to Moore (2013), where each of the three sounds was amplitude modulated by a 6 Hz sine wave set to one of four modulation depths: 0.25 (25%), 0.50 (50%), 0.75 (75%) and 1 (100%). Additionally, the unmodulated sounds were included as a 0-Hz modulation reference stimulus. All sounds were three seconds in duration and presented using LabVIEW. Sound pressure level (SPL) was adjusted using a programmable attenuator (Model PA5, Tucker-Davis Technologies, Florida, USA) to give 70 dB SPL at the eardrum. The sounds were routed through a headphone driver (HB7, Tucker-Davis Technologies, Florida, USA) and presented to the participant via insert earphones (ER2, Etymotic Research Inc., Illinois, USA).

2.3 Noise sensitivity

Noise sensitivity was measured using the self-report Noise Sensitivity Questionnaire (NoiSeQ: Schutte et al., 2007). This questionnaire consisted of 35 items, where each item asks the respondent to identify their level of agreement regarding each statement on a fivepoint Likert-type scale (1 = strongly agree and 5 = strongly disagree). An average of all items on the scale provides a measure for a global noise sensitivity score. As worded, lower scores indicate greater sensitivity whereas higher scores represent greater resistance to noise.

2.4 Procedure

The study consisted of two parts, a behavioural component and a passive component coinciding with EEG. For the behavioural component, participants rated the annoyance of the 15 sounds using Ando's (2001) paired comparison test. Here, a sequence of paired sounds is randomly presented to a participant who then judges which of the pair was the most annoying. Participants were seated comfortably in a sound-attenuating chamber in front of a monitor as they listened to the 105 pairs of sounds, indicating which of the pair (1st or 2nd) was the most annoying. The experiment was approximately 45 minutes in duration, and each pair of sounds never occurred twice during the experiment, each sound was never paired up with itself, and a different sequence of randomly selected pairs of sounds was generated for each participant. The inter-stimulus interval between a pair of sounds was 500 ms.

For the passive component, the participants were first fitted with an 128–channel Ag/AgCl electrode net (Tucker, 1993; Electrical Geodesics Inc., Eugene, Oregon, USA) which recorded scalp activity at 250 Hz (0.1–100 Hz analogue bandpass) using Electrical Geodesics Inc. amplifiers (200-MΩ input impedance). Electrode impedances were kept below 40 kΩ and the common vertex (Cz) was used as reference. Participants were then seated in an electrically shielded room (Model L3000; Belling Lee, Enfield, England) approximately 57 cm in front of a monitor displaying a cross on which they were instructed to fixate to minimize eye-movement artefacts. Participants were instructed to remain as still as possible and listen to the sounds passively while having their scalp potentials recorded. The session was divided into two blocks, and participants were given a short break between them. In each block, all sounds were presented in groups according to their sound type: chord, noise and tone. Each sound group was presented once in each block in random order. Within each sound group, the five modulation depths were repeated seven times each, giving 35 presentations per block. In total, 210 sounds were presented to the listener in one session. The order of sound presentation was randomized for each participant. The interval between each member of the pair (i.e., the inter-stimulus interval) was set at 500 ms, while the interval between each pair (i.e., inter-trial interval) was drawn from a rectangular distribution between 5000 ms and 7000 ms.

2.5 Data analysis

All statistical analyses were conducted using the Statistical Package for Social Sciences (v.25, SPSS Inc., Chicago, IL, USA). The sound annoyance data obtained from each participant were analysed to produce a grand annoyance score across all 15 sounds, and an annoyance score for each amplitude modulation depth within the same sound type. First, a general annoyance score for each sound was calculated by counting the number of times each sound was selected as the most annoying and divided by the number of times the sound was presented in a pair (here 14 times). Consequently, a grand annoyance score was calculated for each participant. Now turning to the calculation of annoyance scores across modulation depth, but within a sound type, the number of times each modulation depth was selected over another within the same sound type was counted and then divided by four. Statistical analyses of the annoyance scores were performed using repeated measures Analysis of Variance (ANOVA), with NS (LNS/HNS) defined as a between-group factor (Group), and both Modulation depth (i.e., 0/25/50/75/100 percent) and Type (chord/noise/tone) as within-group factors.

The EEG recordings were segmented into 3000 ms epochs (including a 200 ms pre-stimulus baseline). All ocular artefacts were corrected (Jervis et al., 1985) and trials with channels that were marked as bad were dropped from the averaging process. Approximately 97% of the trials survived this process for both groups. Event-related potentials (ERPs) were re-referenced to the mean reference (Cz) and digitally filtered with a zero-phase-shift 3-pole Butterworth filter (Alarcon, Guy & Binnie, 2000) with corner frequencies of 0.1 and 30 Hz. ERPs for individual participants were combined to produce averaged ERPs for each of the experimental conditions across the three sound types.

Electrodes of interest were selected by combining all participant data across the Group, the Types and Modulation. The averaged waveform topographic maps were used to select the electrodes that showed the greatest peaks for the N1, P2 and N2 sites. In order to reduce bias, the same electrodes were used across all three components. Figure 1 shows the electrodes used from each participant over an average time window across that encompassed all three types of sound stimuli over a time window that captured the peak waveform for the N1 (68 – 140 ms), P2 (141 – 272 ms) and N2 (274 -384 ms) components based on the full width half maximum of the area below the peak from the combined group average. The area under the difference waveform curve was used to determine the magnitude for each of the components, for each of the participants. Three 3 x 5 Split-plot ANOVA analyses were conducted separately for N1, P2 and N2 components to examine whether Type (tone, white noise, chord) and Modulation (0/25/50/75/100 percent) within Type differed as a function of Group

(LNS/HNS). When applicable a Bonferroni adjustment was applied, and a lack of statistical significance was taken as *p* >.05. The effect size was measured by partial eta squared (ηρ²).

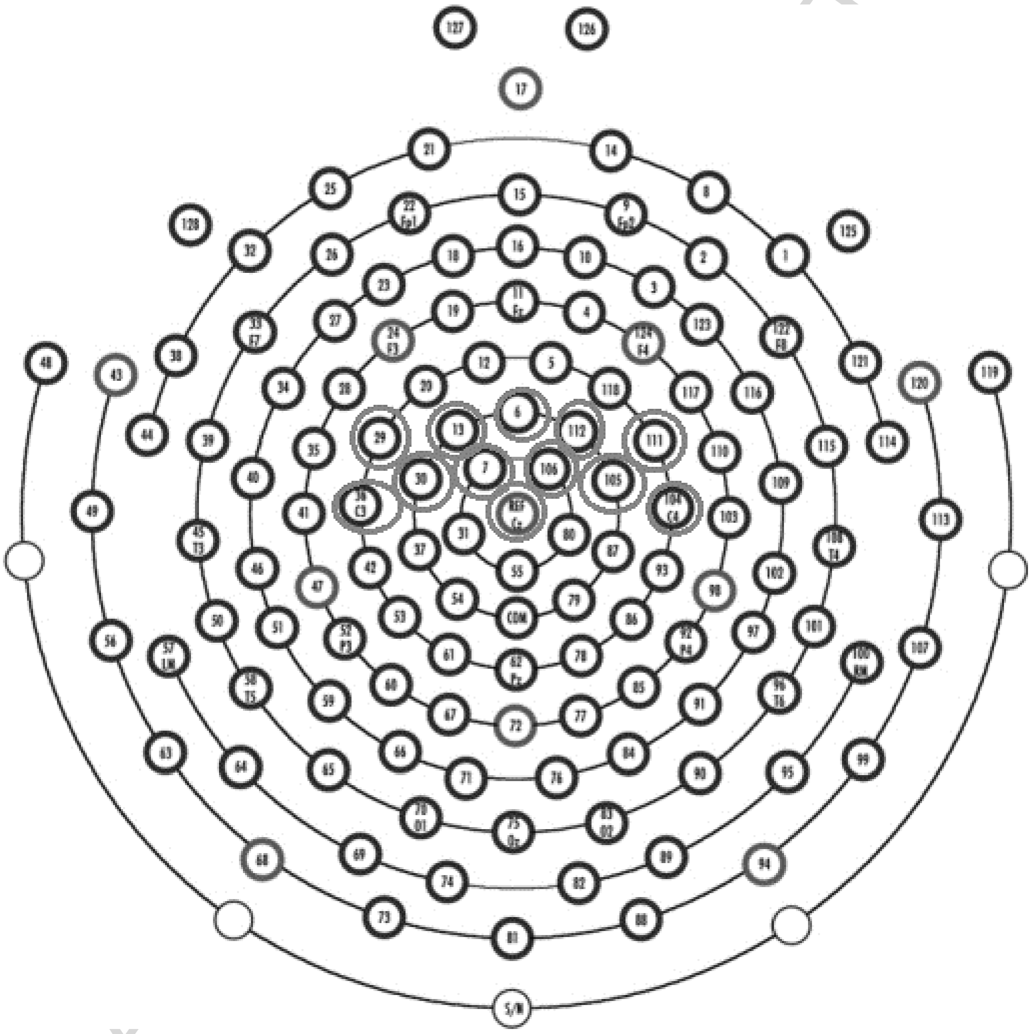

Fig. 1. Head map showing the locations of the electrodes from which N1, P2 and N2 activities were extracted for analysis (electrodes # 6, 7, 13, 29, 30, 36, 104, 105, 106, 111, 112).

3. Results

There was a statistically significant difference in mean NoiSEQ scores across Group ($t(29)=16.29$, $p < .001$), but not across the genders ($p > .05$). Pertinently, the mean NoiSEQ score for the LNS group was 3.62 ($SD = 0.26$) and for the HNS group it was 2.38 ($SD = 0.14$). Additionally, a Pearson correlation analysis indicated no relationship between NoiSEQ scores and age ($r = .12$, $n = 30$, $p = 0.53$). Consequently, gender and age were not considered in the analysis.

3.1 Behavioural Data

Figure 2 plots percentage of times that sound types were selected as most annoying as a function of Modulation. Without reference to Type (Figure 2a), the pooled data indicate increasing annoyance with Modulation, though differences between Group across the three levels of Type (re: Figures 2b – 2d) are visually evident. To document main and interaction effects, a factorial ANOVA was performed with both Type (three levels) and Modulation (five levels) entered as within-group factors, and Group (two levels) added as a between groups factor. The analysis revealed a main effect of Modulation ($F(4,104) = 82.180$, $p < .001$, $\eta_p^2 = .76$), with all Bonferroni-corrected pairwise comparisons being significant (all $p < .001$). No main effect of Group was noted ($F(1, 26) = 1.332$, $p = .259$, $\eta_p^2 = .049$), nor was there an interaction effect between Group and Modulation ($F(4,104) = 1.690$, $p = .158$, $\eta_p^2 = .061$). However, while there was no main effect of Type ($F(2,52) = 0.442$, $p = .645$, $\eta_p^2 = .017$) on annoyance ratings, there was a significant Type x Group interaction ($F(2,52) = 6.012$, $p = .004$, $\eta_p^2 = .188$). Analysis of simple effects indicated no effect of Group upon annoyance ratings for the piano ($F(1,26) = 1.826$, $p = .188$, $\eta_p^2 = .066$) or white noise ($F(1, 26) = 4.080$, $p = .056$, $\eta_p^2 = .136$) sounds, but an effect was found with the tone ($F(1, 26) =$

11.552, $p < .001$, $\eta_p^2 = .308$). Here, *post hoc* tests revealed statistical significance ($p < .05$) between the two groups for all but the zero modulation depth.

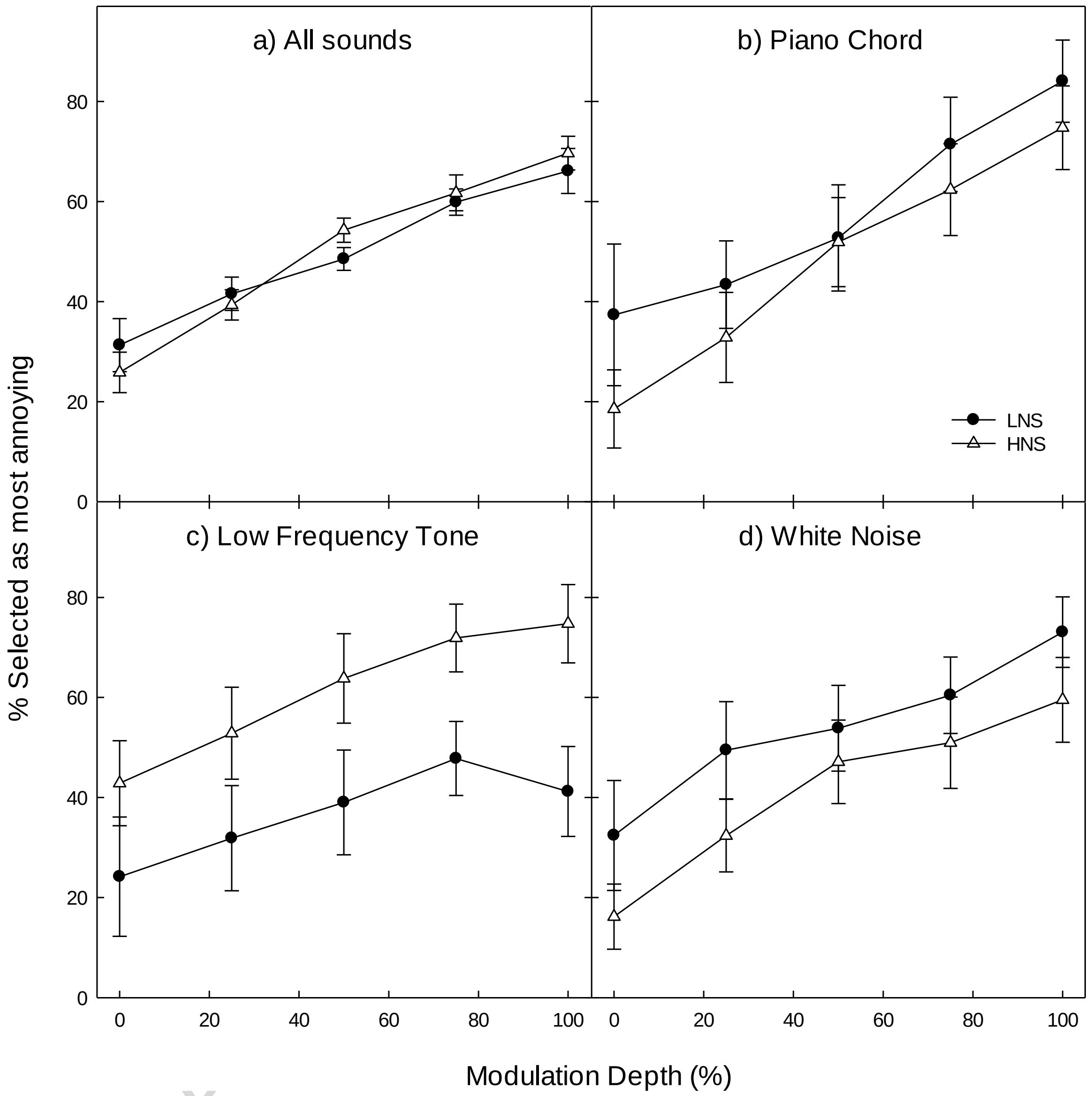

Fig. 2. Percentage of times the sound was judged the most annoying of the pair as a function of Modulation depth (%) for the low noise sensitivity (LNS) and high noise sensitivity (HNS) groups. Bars represent 95% confidence intervals.

3.2 EEG Data

Three 2 x 3 x 5 Split-plot ANOVA analyses were conducted for N1, P2 and N2 components to examine whether Type (tone/noise/chord) and Modulation (0/25/50/75/100%) within Type differed across Group (LNS/HNS). Auditory ERP components of interest are presented in order of time occurrence, and an example ERP is presented in Figure 3.

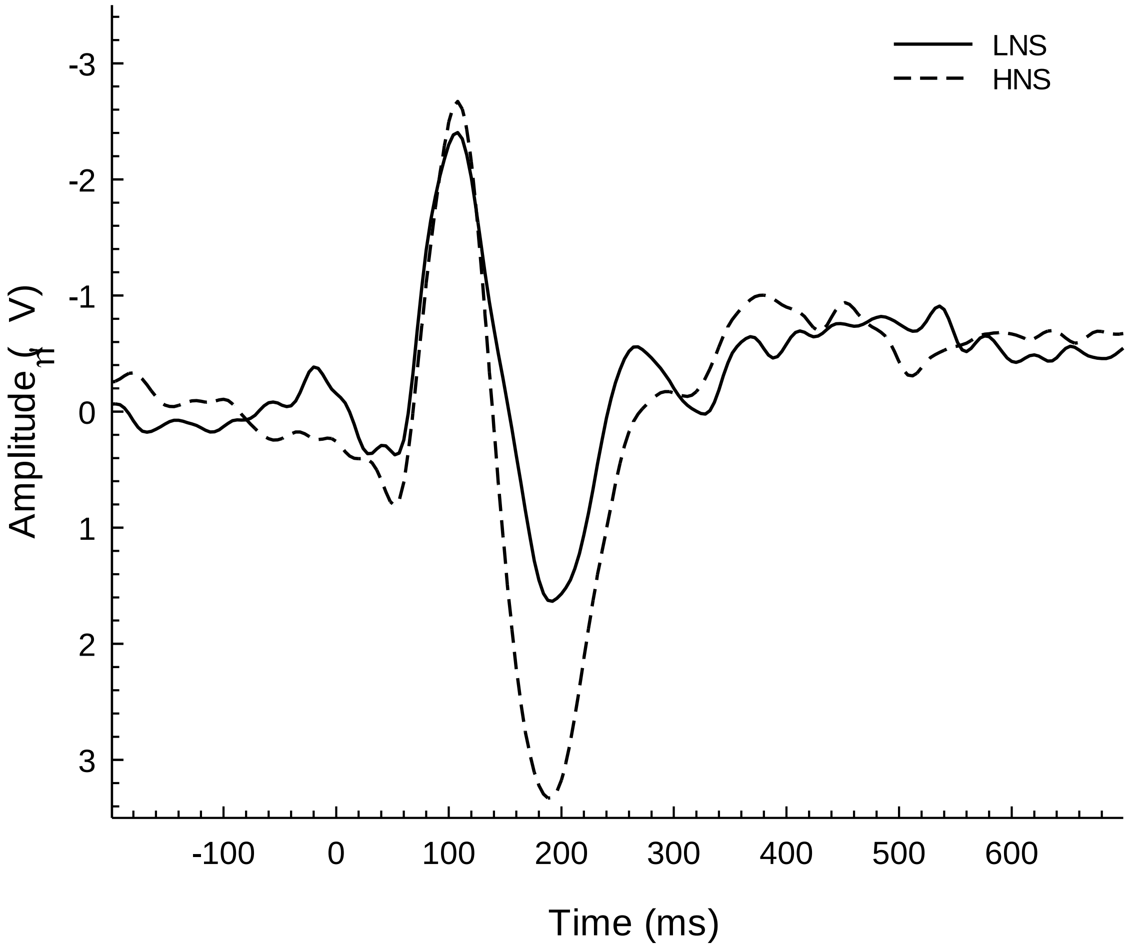

Figure 3: Group average event-related potential waveforms for the low frequency tone plotted for both low noise sensitivity (LNS) and high noise sensitivity (HNS) groups.

3.2.1 N1 component

There was a significant effect of Modulation ($F(4,104) = 6.659$, $p < .001$, $\eta^2_\rho = .20$) upon the N1 component. In Figure 4a significant differences can be seen between the 0% and both the 75% and 100% modulation depths. N1 amplitude differences were also observed between modulations of 25% and 75%, while the difference between the 25% and 50 % modulations were close to significance ($p = .055$) for the N1 component. Remaining main effects of Group, and Type were not significant ($p > .05$). All interactions, including between Group were not significant ($p > .05$) as shown in Figure 4b, however, the Type x Group interaction approached significance ($F(2,52) = 2.78$, $p = .071$, $\eta^2_\rho = .10$).

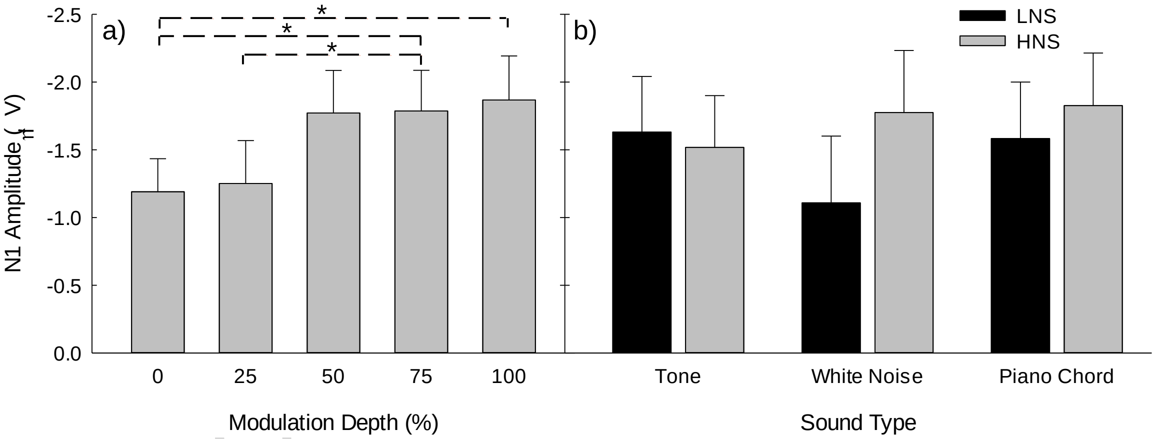

Fig. 4. Panel (a) shows the overall amplitudes for each Modulation depth for the N1 component. Panel (b) shows N1 amplitudes as a function of sound type for the LNS and HNS groups. Significant differences are indicated by *.

3.2.2 P2 component

There was a significant effect of Modulation (*F*(4,104) = 5.87, $p < .001$, $\eta^2_{\rho} = .18$) on the P2 component. Figure 5a shows a significant difference between the 0% and 25%, 75%, and 100% Modulation depths, while the difference between the 0% and 50% depths was approaching significance ($p = .055$). Effects of Group and Type were not significant ($p > .05$). However, a Group x Type interaction was observed (*F*(2,52) = 3.64, $p = .033$, $\eta^2_{\rho} = .12$). Figure 5b shows significant amplitude differences between the LNS and HNS groups for the tone. Group differences were not found for the white noise ($p = .623$) nor the chord ($p = .450$). A Group x Type x Modulation interaction was found (*F*(8,208) = 2.31, $p = .022$, $\eta^2_{\rho} = .08$). Figure 6 shows significant differences between the LNS and HNS groups for the tone at both the 50% and 100% Modulation depths. All remaining differences for Modulation were not significant for the tone for the P2 component. Group differences were not found for the white noise or the chord across modulations (all *p*'s > .05).

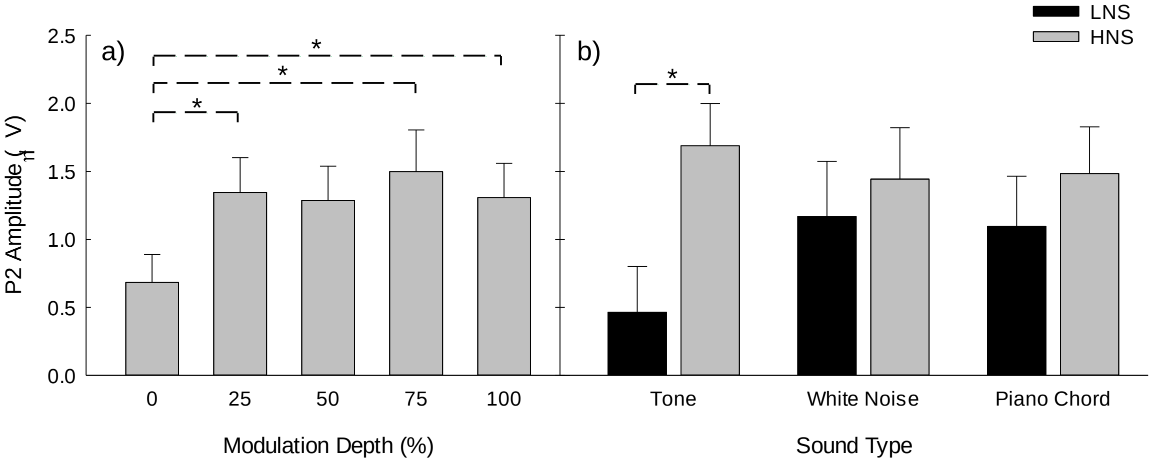

Fig. 5. Panel (a) shows the P2 amplitudes across Modulation depths and Panel (b) across Sound type for the LNS and HNS groups. Significant differences are indicated by *.

3.2.3 N2 component

For the N2, there are no significant effects for Group (*F*(1,26) = 5.39, *p* = .591, η^2_ρ =.01); Type (*F*(2,52) = 1.06, *p* = .355, η^2_ρ = .04); or Modulation (*F*(4, 104) = 0.17, *p* = .955, η^2_ρ = .01). However, a Group x Type x Modulation interaction was obtained (*F*(8,208) = 2.22, *p* = .027, η^2_ρ = .08), as shown in Figure 7. For the white noise, Group differences were found at the 25% and 50% Modulation depths. The remaining Modulation depths (0%, 75% and 100%) for the white noise did not show significant differences across Group, nor did any Modulation depths for the tone or the chord. All remaining interactions were not significant (all *p* > .05).

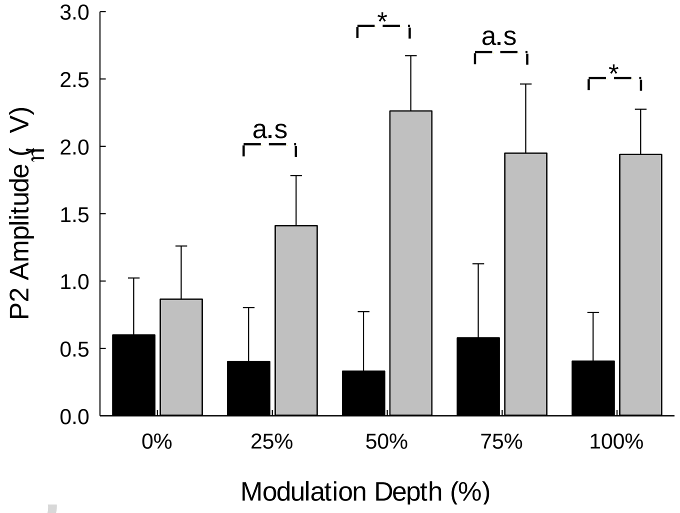

Fig. 6. P2 amplitudes for each Modulation depth for the tone for both low noise sensitivity (LNS) and high noise sensitivity (HNS) groups. Significant differences ($p < .05$) are indicated by the *,where a.s = approaching significance.

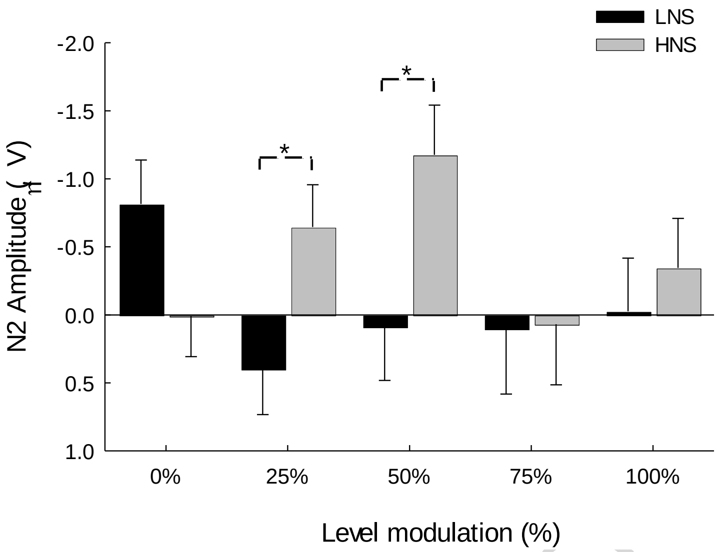

Fig. 7. N2 amplitudes for noise as a function of modulation depth for both low noise sensitivity (LNS) and high noise sensitivity (HNS) groups. Significant differences (*p* < .05) are indicated by the asterisks.

4. Discussion

In summary, the aim of this study was to compare early ERP components across individuals reporting low (LNS) and high (HNS) levels of noise sensitivity. The finding that low frequency tones were rated as especially annoying to those in the HNS group is novel. Furthermore, no significant differences between the LNS and HNS groups were noted in N1 amplitudes across the three sound types. However, P2 amplitudes were significantly greater for the HNS group compared to the LNS group, but only for tlow frequency tones. Specifically, with the exception of the unmodulated tone, the HNS group was associated with greater P2 amplitudes across the four modulation depths. Finally, N2 amplitudes at the 25% and 50% modulation depths were statistically greater for the HNS group. These findings will now be elaborated upon.

An interesting finding of this study is the generally linear relationship between annoyance and modulation depth. To date, only weak relationships between annoyance and both sound level and frequency have been reported, while temporal parameters such as modulation have been largely neglected in the noise literature (Dittricha & Oberfeld, 2010). Berglund (1998) reported noise with large amplitude fluctuations as especially annoying, noting that habituation to fluctuating noise was unlikely. Laming (1986) argued that because the auditory system is differentially, as opposed to directly, coupled to acoustic stimuli, humans have increased sensitivity to modulated sounds. Taken together, our data suggest that amplitude modulation has a potent effect on annoyance responses, increasing annoyance by up to 130%.

We found a significant effect of modulation upon the N1, whereby the N1 increased if sounds were modulated. While a positive association between other stimulus features (e.g., amplitude) and the N1 have been broadly reported in the literature, our study appears to be the first to specifically report the effect of amplitude modulation. A further finding relating to amplitude modulation is the apparent invariance in early ERP components once modulation has been applied (i.e., > 0%). For the N1 component (*re:* Figure 4), amplitudes were equivalent across the 0% and 25% modulation depths, and across the 50%, 75% and 100% depths, creating a step function of sorts. For the P2 (*re:* Figure 5) the amplitude approximately doubles between 0% modulation and the rest (i.e., 25% to 100%). The evidence seems to suggest that the degree of modulation depth is not an important influence on early ERP components, and instead it is the presence of modulation *per se* that is important. Interestingly, the proportional relationship between modulation depth and annoyance (*re*: Figure 2) indicates that the step-like functions found with early ERP components such as the N1 and P2 may not be useful predictors of annoyance levels.

Considering aggregate behavioural data (i.e., Figure 2a), it was found that the annoyance responses across the range of sound types and modulation depths did not differ across LNS and HNS individuals. This indicates that Ando's (2009) paired comparison test was effective in eliminating the influence of negative affect on pooled ratings. However, a significant difference between the two groups was noted for the low-frequency tone. This is an interesting finding, as audiometrically, NS has not been linked to increased auditory acuity (Ellermeier et al., 2001) nor to differences in the bottom-up processing of auditory features such as frequency (Kliuchko et al. 2016). In an evolutionary scheme low-frequency sounds are more likely to signal the presence of a threat than high-frequency sounds (Heffner, 2004), and are associated with serious health effects (Leventhall et al., 2003). This sensitivity to low-frequency tones may relate to an individual's evolutionary history, with NS having a heritability estimate of 36% (Heinonen-Guzejev et al., 2005), and anatomical differences in the cochlear able to substantially increase the ear's sensitivity to low frequencies (Salt, Brown, Hartsock, & Plontke, 2009). Of interest is to examine if ERP components obtained with the low-frequency tone differ across the LNS and HNS groups, and discussion now turns to this.

Based on our data it is observed that the LNS group has lower P2 amplitudes overall than the HNS group, suggesting that the HNS individuals may be automatically attending to sound regardless of its relevance. The absence of a main effect of NS on the N1 was noted, indicating that low-level feature processing is unlikely to be different between the two groups, a finding that is consistent with audiometric data. Interestingly, the group difference is most notable for the low-frequency tone, with the HNS group showing a larger P2 amplitude compared to the LNS group. The P2, which overlaps the P3, reflects preattentive stimulus processing that subsequently guides attention to task-relevant stimuli (Luck & Hillyard, 1994), and is larger for stimuli containing target features. Thus, it may be that, for the low-frequency tone, high NS individuals are over-processing irrelevant stimuli at early stages, and the larger P2 amplitudes indicate deficits in the capacity to withdraw attentional resources from the stimuli. A study by Priplfi et al. (2006) likewise demonstrated that the P2 was pronounced in women susceptible to annoyance responses to fMRI scanner noise, while Shepherd et al. (2016) also reported the likelihood of filtering deficits in individuals with higher levels of NS.

For the N2 component, significant differences at the 25% and 50% modulation depths were noted between the LNS and HNS groups. The N2 is thought to represent a number of underlying cognitive processes, including stimulus identification and attentional shifts (Patel & Azzam, 2005). Speculatively, the differences in N2 between the LNS and HNS groups may reflect the greater annoyance exhibited by the HNS group to the low and mid-range depths of modulated noise, while the LNS individuals only begin to exhibit equivalent levels of annoyance for higher levels of modulation. However, with reference to our annoyance rating data (*re:* Figure 2), there were no significant differences in annoyance ratings between the two groups at these levels. Irrespective of the behavioural data, the general trend presented in Figure 7 indicates that the advent of modulation increases N2 amplitudes in the HNS group. However, the exact cognitive processes responsible for this increase in N2 amplitude cannot be determined using the data from this study, and further research is called for regarding this matter.

Our data and others (e.g., Kliuchko et al. 2016) indicate that highly noise sensitive individuals may have deficits in the segregation of signal from noise, and consequently higher-order compensatory mechanisms need to be deployed. Considering the Effortfulness

Hypothesis, feature extraction in the form of higher-order auditory scene analysis may require more ‘listening effort’ (McGarrigle et al., 2014) as the filtering processes indexed by the P2 become dysfunctional. Specifically, the recruitment of top-down attentional mechanisms involving ‘selective gain’ (McGarrigle et al., 2014) allows signals to pop out from the noise. Consequently, this increase in cognitive load may underlie annoyance responses, with auditory-related sensory overload representing the extreme on the continuum whereby annoyance becomes distress. Using magnetoencephalography, Kliuchko et al. (2016) reported that NS was linked to altered sound feature processing and further hypothesised that the auditory processing difficulties experienced by NS individuals led them to negatively evaluate the soundscapes they encounter in their daily lives.

Similarly, adverse noise sensitivity is commonly reported in individuals with ASD, and can be highly distressing for individuals (Alcantara, Weisblatt, Moore & Bolton, 2004; Landon, Shepherd, & Lodhia. 2016). Difficulty segregating out target sounds from background noise is evident in the ASD stream segregation literature, with some studies demonstrating reduced amplitudes in the P2 region (Lepisto et al., 2009; Lodhia et al., 2017) and others not (Ceponiene et al., 2003; Lepisto et al., 2008), though these disparities in results are likely due to methodological differences. However, auditory overload in this group might also be explained by cognitive load. A recent study by Remington & Fairnie (2017) suggests that individuals with ASD have increased perceptual capacity that captures more information about the environment compared to neuro-typical controls. The ‘Load theory of attention and cognitive control’ (Lavie, 2005) argues that tasks with high perceptual load eliminate the capacity for distractors to be processed, while those with low perceptual load allow for ‘extra’ processing of irrelevant information. In ASD this over-processing leads to sensory overload (Remington & Farinie, 2017). Speculatively, a similar process may have occurred in our HNS group, where their capacity for processing or attending to irrelevant information is larger compared to individuals that those in the LNS group.

A key objective of our study was to judge the viability of the Information Processing Hypothesis of NS. Our annoyance data indicates that the paired comparison test was effective in controlling for a negative affective bias. Arguably then, differences in early ERPs should serve to indicate processing differences between those in the LNS and HNS groups. Our data suggest that a stimulus-orientated approach to NS cannot be neglected, with the low-frequency tone eliciting greater annoyance in HNS individuals compared to the LNS individuals. For this stimulus, the HNS group exhibited both greater annoyance and greater P2 amplitudes. However, no differences in P2 were observed between the two groups with the white noise and the piano chord. It is therefore open to conjecture that for some as yet unknown reason some individuals are susceptible to low-frequency tones, but the failure to uncover significant differences between the two groups in terms of N1 amplitudes at least eliminates the potential for our results to reflect misophonia (Schröder et al., 2014).

The findings of this study should be interpreted with reference to its limitations. The first limitation is that the selection of a non-clinical sample may serve to under report the true effect of NS upon early ERP components. On the other hand, a non-clinical sample affords a more valid comparison between the two groups due to the absence of other clinical symptoms that can impact ERP components. Secondly, the lack of an association between NS and age in the current data is not consistent with the literature (Heinonen-Guzejev et al., 2011) and may reflect the limited variability in the age of our participants. Thirdly, it may be that NS is associated with multiple pre-attentive processes along the auditory cascade, and so future research is required to identify if subtypes of NS exist and, if so, how these relate to these different processing steps. Further, rather than undertaking group-level analyses, future research could recruit participants across the NS spectrum, and correlational analysis between NS and ERP indices performed.

In conclusion, annoyance to modulated sounds is reflected in both the P2 and N2 of the EEG. Furthermore, our data reinforce previous studies (e.g., Kliuchko et al. 2016) suggesting that electrophysiological indices can be used to differentiate individuals along the NS continuum. In response to a low-frequency tone, the amplitude of the P2 component was higher in our highly noise-sensitive group, and thus the P2 may index a pronounced reactivity to this type of sound.

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Highlights.

1. Noise sensitivity is poorly understood but over-represented in clinical populations.
2. The N1, N2 and P2 are associated with the amplitude modulation of sounds.
3. Noise sensitivity may reflect dysfunctional filtering as indexed by the P2 and N2.
4. Over-processing may increase cognitive load in noise sensitive individuals.
5. Noise sensitivity has psychophysiological markers.