



Is it too loud? Ask your brain!

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ABSTRACT

Purpose: In this study, the objectification of the subjective perception of loudness was investigated using electroencephalography (EEG). In particular, the emergence of objective markers in the domain of the acoustic discomfort threshold was examined.

Methods: A cohort of 27 adults with normal hearing, aged between 18 and 30, participated in the study. The participants were presented with 500 ms long noise stimuli via in-ear headphones. The acoustic signals were presented with sound levels of [55, 65, 75, 85, 95 dB]. After each stimulus, the subjects provided their subjective assessment of the perceived loudness using a colored scale on a touchscreen. EEG signals were recorded, and afterward, event-related potentials (ERPs) locked to sound onset were analyzed.

Results: Our findings reveal a linear dependency between the N100 component and both the sound level and the subjective loudness categorization of the sound. Additionally, the data demonstrated a nonlinear relationship between the P300 potential and the sound level as well as for the subjective loudness rating. The P300 potential was elicited exclusively when the stimuli had been subjectively rated as "very loud" or "too loud".

Conclusion: The findings of the present study suggest the possibility of the identification of the subjective uncomfortable loudness level by objective neural parameters.

1. Introduction

We are all familiar with the concept of loudness, yet it is difficult to quantify. Determining sound levels is an everyday measurement. Understanding why a baby's cry is perceived as loud but our favorite music is not is difficult to capture with physical quantities. Nevertheless, the subjective perception of loudness is an important parameter in psychoacoustics.

Measuring the perceived loudness, especially the upper limit, the so-called uncomfortable level, above which an acoustic stimulus is perceived as too loud, is of high relevance in the fitting of hearing aids and hearing implants (e.g. cochlear implants, active middle ear implants, bone anchored devices) to the hearing impaired patient (Byrne et al., 2001; Hodges et al., 1997; Moore and Glasberg, 2007; Mueller, 2011; Pieper et al., 2021; Stephan and Welzl-Muller, 2000). Hearing aids and hearing implants rely on the determination of the lower level (hearing threshold) and an upper level of stimulation. This upper level can be referred to as the uncomfortable level (UCL). These measures define the boundaries of stimulation in hearing aid and hearing implant treatment.

Usually, those levels are determined by subjective feedback from the patients (Mueller, 2011; Punch et al., 2004). Such techniques, however, require the patient to have the cognitive and physical abilities to report the perceived loudness accurately. That is not the case in babies or toddlers, for instance. Prenatal deaf or patients with severe hearing loss are treated with hearing aids from 2 to 3 months (Joint Committee on Infant Hearing, 2007; Sininger et al., 2009) onwards or hearing implants from below 24 months (Liu et al., 2019; Nicholas and Geers, 2007). The fitting of such patients relies in most cases on empirical models in combination with audiometric test results for hearing aids (Byrne et al., 2001; Scollie et al., 2005) or on the estimation of the upper threshold based on electrical measures in cochlear implants (Alvarez et al., 2010; McKay et al., 2013; Van Den Abbeele et al., 2012) and the experience of the audiologist.

Objective measures such as the stapedius reflex (Stephan and Welzl-Muller, 2000; Van Den Abbeele et al., 2012) can be used to determine an upper stimulation level that elicits a sound sensation rated by most listeners as loud but not too loud. Measuring the stapedius reflex requires the patient to accept the measurement device (earplug), sit still without making noises, and have an anatomically normal middle ear,

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which makes such a technique unusable for example for children with cleft palate.

A group of methods that bear the potential to be used as objective measures in audiology are neurophysiological methods such as electroencephalography (EEG). Several studies have demonstrated a correlation between electrophysiological measures and sound perception (Barry et al., 2022; Billings et al., 2007; Cass and Polich, 1997; Legris et al., 2022; Mulert et al., 2005; Potter et al., 2017; Ruohonen et al., 2020; Soeta and Nakagawa, 2012; Sugg and Polich, 1995). Electrophysiological correlates provide important insights into neural processing mechanisms as they provide a high temporal resolution in the range of milliseconds. The event-related potentials (ERP) N100, P200, N200, and P300 components were identified as crucial for auditory processing (for a review on auditory ERPs, refer to Joos et al. (2014)).

The N100, P200, N200, and P300 components have been found to correlate with the presented sound pressure level of acoustic stimuli (Barry et al., 2022; Billings et al., 2007; Cass and Polich, 1997; Legris et al., 2022; Paiva et al., 2016; Potter et al., 2017; Sugg and Polich, 1995). The auditory N100 (around 60–150 ms) was mainly found in response to sound detection (Barry et al., 2022; Billings et al., 2007; Legris et al., 2022; Mulert et al., 2005; Näätänen and Picton, 1987; Parasuraman and Beatty, 1980; Potter et al., 2017; Sugg and Polich, 1995; Winkler et al., 1997) while the P200 (around 150–250 ms) reflects stimulus classification, attention allocation, perceptual learning, and even memory processes (Arnott et al., 2011; Barry et al., 2022; Billings et al., 2007; Legris et al., 2022; Sugg and Polich, 1995; Sur and Sinha, 2009). The N200 potential, appearing around 200–350 ms, was often found to be associated with cognitive control and inhibition processes (Billings et al., 2007; Davies et al., 2009; Paiva et al., 2016; Sugg and Polich, 1995) which might, for example, play a role in loudness rating. The P300 potential (250–500 ms) is a late ERP component associated with attentional processes to evaluate the importance or salience of an event (Cass and Polich, 1997; Polich, 2003; Sugg and Polich, 1995). All these components were found to increase in amplitude and sometimes decrease in latency with increasing sound levels (Davies et al., 2009; Paiva et al., 2016). Most of EEG studies investigating increasing sound levels presented pure tones (500 or 1000 Hz) in a passive listening paradigm in which mostly young normal-hearing subjects did not have to perform any task (Barry et al., 2022; Billings et al., 2007; Potter et al., 2017). Interestingly, Mulert et al. (2005) also used pure tones at 1000 Hz at sound pressure levels of 60, 80, and 100 dB HL, presented passively in a random order to young normal-hearing volunteers. However, authors did not only measure electrophysiological correlates with EEG but simultaneously also assessed brain activation in the primary auditory cortex by means of functional magnetic resonance imaging (fMRI). The study focused above all on the N100 peak in the EEG, measured at Cz. The study found a linear correlation between the sound level dependent N100 potential in the EEG and sound level-dependent fMRI activation of the auditory cortex.

Not only passive listening paradigms were employed to investigate ERPs underlying sound levels of acoustic stimuli but also active paradigms which require subjects to perform a specific task, mostly by pressing a button. Most of these studies adopted the so-called oddball paradigm, in which subjects have to actively press a button in response to rare target stimuli (usually presented about 20% of the time compared to frequent standard stimuli presented in 80% of the cases). In such paradigms (Sugg and Polich, 1995) increasing amplitudes and decreasing peak latencies in particular of the P300 component were found with increasing sound pressure levels (Cass and Polich, 1997; Sugg and Polich, 1995).

The P300 potential is a known indicator of attentional mechanisms. Thus, loud stimuli will attract more attention and as a consequence lead to increased P300 amplitudes. As described by Snyder and Polich (Polich, 2007; Snyder and Hillyard, 1976), the P300 can be divided into a frontal P3a and a parietal P3b component. The P3a component shows its maximum at 258 ms, whereas the maximum of the P3b component

appears later around 378 ms (Snyder and Hillyard, 1976). The P3a component is believed to reflect an automatic switch of attention to unexpected stimuli (Polich, 2003). In contrast, the P3b is believed to be elicited by conscious attention-drawing processes such as memory processing and context updating operations (Polich, 2003). Thus, a P300 was found in healthy subjects when detecting acoustic warning signals (Dehais et al., 2019; Giraudet et al., 2015) but was absent in high mental workload situations, where the acoustic stimulus was overheard or missed (Dehais et al., 2019). Further, the P3b was found to react not only to the predetermined probability of a stimulus category but also to the subjectively and attentively perceived probability (Courchesne, 1977). This aspect is especially relevant for the present study, as neural correlates of subjective loudness perception will be investigated. Attention is an important aspect in the perception of acoustic stimuli and is of particular importance when sounds are perceived as very loud.

To summarize, several ERP components can reliably indicate increasing sound pressure levels, however, in order to identify the uncomfortable level of an acoustic input, the subjective perception of how loud/uncomfortable a sound is has to be combined with objective neural parameters. To our knowledge, however, no neurophysiological study directly analyzed ERPs elicited by different subjective loudness categorizations. Thus, the exact neural mechanisms reflecting the audio-logical discomfort threshold are still not sufficiently understood.

In this study, we aim to close this gap by using noise stimuli at different sound levels that have the potential to reach the auditory uncomfortable level. In particular, we expect to find a linear relationship between the N100 and the sound pressure level. Apart from the relationship between predetermined loudness, the innovative aim of this study concerns the investigation of ERPs for subjective loudness, varying across individuals. By collecting feedback on the subjectively perceived loudness after each acoustic stimulus and analyzing the EEG signal time-locked to sound presentation based on this subjective loudness rating rather than the predetermined sound pressure level, the present study aims to assess brain parameters in the EEG objectively assessing subjective loudness perception and thus point out the individual uncomfortable loudness level identified by the brain.

We opted to study noise stimuli instead of pure tone stimuli, as real-world acoustic environments generally consist of multiple frequencies rather than single tones. Furthermore, we did not use narrow band stimuli because of the varying level loudness relationship across different center frequencies. Based on the discussed literature we hypothesize, that the N100 component exhibits a linear relation to the sound level of the presented stimuli. We assume that an acoustic stimulus that is perceived as uncomfortably loud may show effects on later components such as the P200 and P300. The P200 component might potentially show a relation with the uncomfortable level, based on its stimulus classification and attention allocation properties. Similarly, we hypothesize that a P300, due to their attention-drawing characteristics, might play a major role in detecting subjective auditory uncomfortable levels.

2. Materials and methods

The present study was approved by the local ethics committee of the Medical University of Innsbruck (no. 1337/2021). Informed written consent was obtained from all participants before the investigation began.

2.1. Participant cohort

14 female and 13 male participants, with a mean age of 24 (2.6) years, have been recruited for the present study. The inclusion criteria were age between 18 and 30 years, right-handedness, no neurological disorders, normal or corrected-to-normal vision, and normal hearing. The Oldfield Handedness Inventory checked the handedness (Oldfield, 1971), and normal hearing was checked at our Department for Hearing,

Speech, and Voice Disorders at the Medical University of Innsbruck. All subjects had to undergo a professional ear examination, followed by pure tone audiometry and impedance measurement of the eardrum to check the function of the middle ear. The median PTA4 (average over the pure tone thresholds at 500, 1000, 2000 and 4000 Hz) hearing threshold of the test group was at 5 dB HL with an interquartile distance of 5 dB HL.

2.2. Experimental setup

2.2.1. Stimuli and test procedure

In the experiment, a CCITT (Comité Consultatif Internationale Télégraphique et Téléphonique) noise burst with frequencies ranging from 100 to 6000 Hz of 500 ms duration and a ramp on of 5 ms was presented as an acoustic stimulus. The stimulus was delivered to the participant's right ear by in-ear headphones (3 M E-A-Rtone 3A). This presentation mode was selected in order to provide the best hearing conditions in right-handed normal-hearing subjects assumed to benefit from a right-ear-advantage (Spellacy and Blumstein, 1970; Studdert-Kennedy and Shankweiler, 1970). We decided against a dichotic listening paradigm in which two different sounds are presented to the two ears, as we wanted to avoid effects of binaural loudness summation and potential interference of individual attentional capacities. The noise stimulus was presented at five different sound pressure levels [55, 65, 75, 85, 95] dB HL in pseudo-random order (maximal two consecutive equal sound level repetitions, maximal two single step size changes e.g. from 55 to 65 dB). Every sound pressure level was presented 40 times, which, in total, equates to 200 stimulus presentations. Before the stimulus presentation, a 500 ms fixation cross was shown on the screen about 1 m in front of the subjects. This fixation cross remained still visible during the sound presentation. After each sound, the participants gave subjective feedback on the perceived loudness level using a colored scale on a touchscreen, as shown in Fig. 1a. The participant's answer was recorded on a discrete scale determined by the horizontal extension of the color bar. After the subject's feedback, the inter-stimulus-interval (ISI) followed by presenting a fixation cross on the touchscreen for a mean duration of 12 s (8 to 16 s), and the test subjects were instructed to focus on it. The answers of the participants have been divided into 8 segments of answers [A1, A2, A3, A4, A5, A6, A7, A8], where segment, corresponding to answer A1, indicates the "not heard", and segment 8, corresponding to answer A8, indicates the highest possible answer, i.e. "too loud" (Fig. 1b).

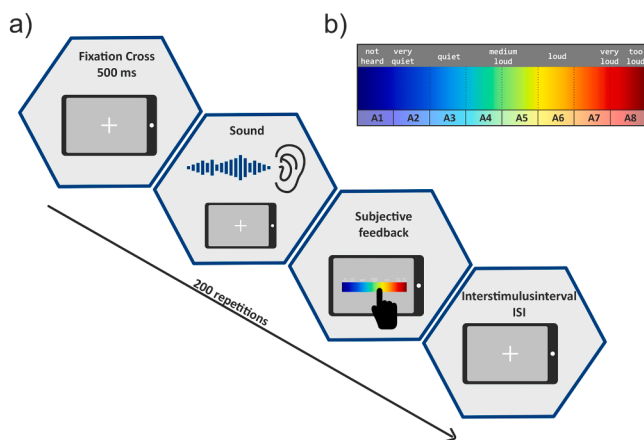


Fig. 1. Schematic representation of one experimental trial (a). After an initial fixation cross is displayed on the touchscreen (500 ms), the acoustic stimulus is presented. After the presentation, the subjects can enter their subjective assessment using the touchscreen. This is followed by an interstimulus interval lasting on average 12 s (8–16 s randomly distributed). For evaluation, the response scale is divided into 8 segments (b).

In this study, we focused on the analysis of EEG measurements, although the experimental paradigm was originally designed to accommodate both EEG and fNIRS data collection. To optimize the fNIRS measurements, the interstimulus interval (ISI) was extended to 8 to 16 s, which allowed for sufficient hemodynamic response. While the fNIRS data are not included in the present manuscript, the extended ISI remains a feature of the experimental design and is relevant to the interpretation of the EEG results presented here.

2.2.2. EEG recording

The EEG recordings were performed with the BrainAmp System (BrainProducts GmbH, Gilching, Germany) using 9 AgAgCl active electrodes (BrainProducts GmbH, Gilching, Germany) that were placed according to the 10–20 placement system (Jasper, 1958). The electrodes have been placed into a commercially available elastic EEG cap (Easy-Cap, GmbH, Herrsching, Germany) at the positions: F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4. Vertical and horizontal electrooculograms were recorded above the right eye and next to it with electrodes at the positions FP2 and F10, respectively. An electrode placed on the nose of the participants served as an online reference. Position FPz was used as the ground electrode. Each electrode impedance was maintained below 10 k Ω (actiCAP Control, Brain Products GmbH, Gilching, Germany). The EEG signal was measured with the BrainVision Recorder (Brain Products GmbH, Gilching, Germany) software by using a sampling frequency of 1000 Hz (amplified between 0.016 and 450 Hz). Before digitalization, the signal was filtered employing the analog/digital converter with an upper cut-off of 450 Hz (24 dB/oct) to prevent aliasing.

2.3. EEG data pre-processing

The EEG data was filtered offline with both a 30 Hz low-pass Butterworth zero-phase filter (slope: 12 dB/oct) and a Notch filter (central frequency: 50 Hz; slope: 12 dB/oct), before segmenting the data from –400 ms to 800 ms relative to the onset of sound. Following the segmentation, the Gratton and Coles algorithm (Gratton et al., 1983) was applied for ocular correction of eye movements and blinking artifacts. In the next step, the data was visually inspected at the segment level. Electrodes displaying significant artifacts, such as spikes or near-zero variance, were removed. As a result of this visual inspection, 7% of the data was removed. Next, a baseline correction was applied at the time window of –400 – 0 ms, followed by a drift correction. The drift correction is based on a 2nd-degree polynomial fit. For the subsequent quantitative analysis, mean amplitudes of the EEG data, time-locked to the onset of sound presentation but coded either according to the sound level or subjective loudness rating, were calculated on a single subject level and as grand averages over all subjects.

2.4. Statistical analysis

For the statistical analysis on a sound level, a rolling ANOVA with the factor sound level (5 levels) on each electrode, with a time window of 25 ms and a step size of 1 ms was calculated. Based on these results, the time windows for the analysis of the N100, P200, and P300 potentials are determined. For this purpose, connected statistically significant time windows that extend over a duration of at least 50 ms are considered. These time windows were analyzed by a two-way ANOVA with the within-subjects factors sound level (55, 65, 75, 85, 95 dB HL) and electrode position (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). Sphericity was tested using Mauchly's Test of Sphericity. Significant main effects of sound level and interactions regarding the sound level were followed by subsequent post-hoc *t*-tests, corrected by employing Bonferroni correction. In addition, the effect sizes between the sound levels have been estimated by calculating Cohen's *d*. The same analyses have also been conducted on a categorical, answer-based subjective loudness level. To assess the linearity of the relationship between the amplitudes of the N100, N200, and P300 potentials and the sound level or subjective

loudness rating, we employed a rainbow test (Utts, 1982). The null hypothesis of the rainbow test indicates a linear relationship between its variables. A significant result from this test indicates a non-linear relationship between the input variables. Further, exemplary results at the single-subject level are presented for the P300 component in order to provide evidence for the robustness of grand average results for the answer-dependent single-subject analysis.

3. Results

The results in this section are presented from the perspective of a sound-dependent and an answer-dependent subjective loudness analysis. The grand average (the average of all trials and all test subjects) of the EEG data for the Cz and Pz electrodes, according to the sound level, is shown in Fig. 2 (an overview of the results of all electrodes is given in the supplement). The grand average for the answer-dependent subjective loudness analysis is shown in Fig. 6. Below the averaged signals, the results of a rolling ANOVA are depicted in a color-coded bar.

Based on the results of this grand average analysis and the discussed literature (Arnott et al., 2011; Folstein and Petten, 2008; Näätänen and Picton, 1987; Parasuraman and Beatty, 1980; Winkler et al., 1997) time windows for the statistical analysis of the N100, P200 and P300 potentials have been selected: from 60 to 150 ms for the N100 potential, 150 – 225 ms for the P200, and 250 – 450 ms for the P300 potential.

3.1. Results for sound-dependent analysis

3.1.1. N100 component (60 - 150 ms)

The results of the two-way ANOVA for the mean amplitude over the N100 time window show a statistically significant main effect for the factor sound level $F(4, 1140) = 11.928$; $p < 0.001$. The interaction between sound level and electrodes did not reach significance $F(32, 1140) = 20.491$; $p = 0.99$. The absolute amplitudes of the N100 potential show an approximately linear dependency (rainbow test $p = 0.27$) of the sound levels, as depicted in Fig. 3 (left). Post-hoc t -test resolving the main effect revealed significant differences between the different sound

levels (Fig. 4 (left)). The 95 dB sound showed a larger N100 amplitude compared to the three lowest sound pressure levels (55, 65, and 75 dB), while the 85 dB sound revealed a larger N100 compared to the two lowest sound levels (55 and 65 dB). The effect size plays an important role in the ability to distinguish two statistically distributed values, in our case, the amplitude of the ERPs regarding the sound levels, from each other. The results of the analysis for the effect size using Cohen's d for the N100 component are shown in Fig. 5 (left). The color map is chosen to reflect the interpretation of the effect size as discussed in (Cohen, 2013; Thompson, 2007), referring to an effect size of ($d = 0.2$) as small, medium ($d = 0.5$), and large ($d = 0.8$). The analysis reveals a medium effect size of up to $d = 0.53$ for the comparison between the two lowest sound levels (55 and 65 dB) with the highest sound level (95 dB).

3.1.2. P200 component (150 - 225 ms)

The P200 component was analyzed in the same manner as discussed for the N100 component above. The results of the amplitude plot reveal no systematic increase/decrease in amplitude between the sound levels (rainbow test $p = 0.01$) (Fig. 3 (center)). The statistical analysis via the two-way ANOVA with the factors sound level and electrode position led to a significant main effect for the factor sound level ($F(4, 1140) = 29.00$; $p < 0.001$) but did not reach a significant result for the interaction between electrode position and sound level ($F(32, 1140) = 0.98$; $p = 0.50$). Subsequent post hoc t -tests resolving the main effect (Fig. 4 (center)) revealed significant results for all stimulus comparisons ($p < 0.001$), apart from the difference between the 65 dB and 95 dB stimulus ($p = 1.0$) and between the 75 dB and 85 dB stimulus ($p = 1.0$). The statistical differences indicate an increase in P200 amplitude from the lowest (55 dB) sound to the 85 dB sound. However, the loudest sound diverges from this increasing pattern as it shows a larger amplitude than the lowest (55 dB) but a smaller amplitude than the 75 and 85 dB sounds. Although there are significant differences between the sound levels, there is no evidence of a systematic dependence from the lowest to the highest sound level. The P200 potential seems, therefore, not suitable for differentiating between the various sound levels, which makes an analysis of the effect size obsolete.

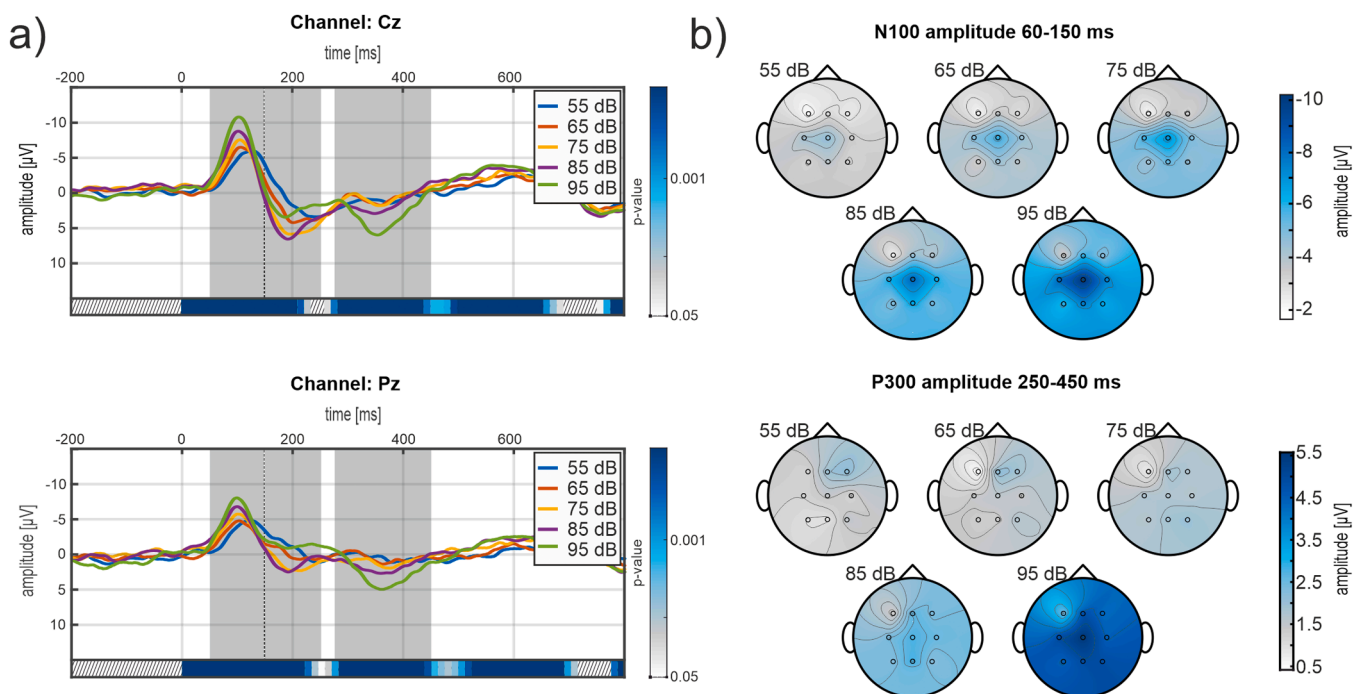


Fig. 2. Grand average of EEG data for sound level at electrodes Cz and Pz (a). Below the EEG curves, the result of a rolling ANOVA (50 ms time window) is shown. The hatched areas show non-significant regions. The gray areas in the EEG data indicate the time window in which an ANOVA was calculated for the N100, P200, and P300 components. Figure (b) shows the topographic maps of amplitude for the N100 and P300 potentials for the different sound levels. Negativity is plotted upwards.

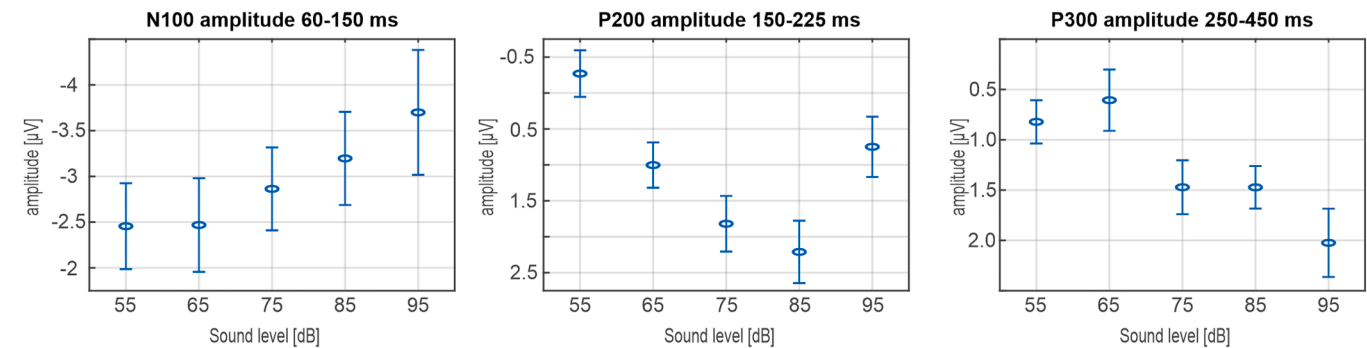


Fig. 3. ERP amplitude plots for the sound level merged over subjects for the N100 (left), P200 (center), and P300 (right) amplitude. The error bars indicate the 99% confidence interval. Negativity is plotted upwards.

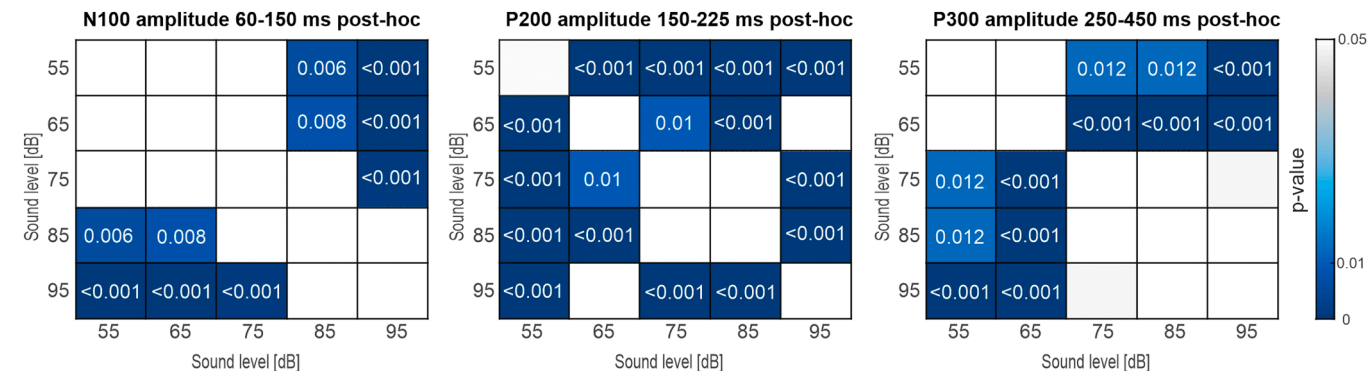


Fig. 4. Results for the post hoc t -test calculation for the N100 (left), P200 (center) and P300 (right) potential in the sound level dependent analysis. Statistically significant results are indicated by their p -values.

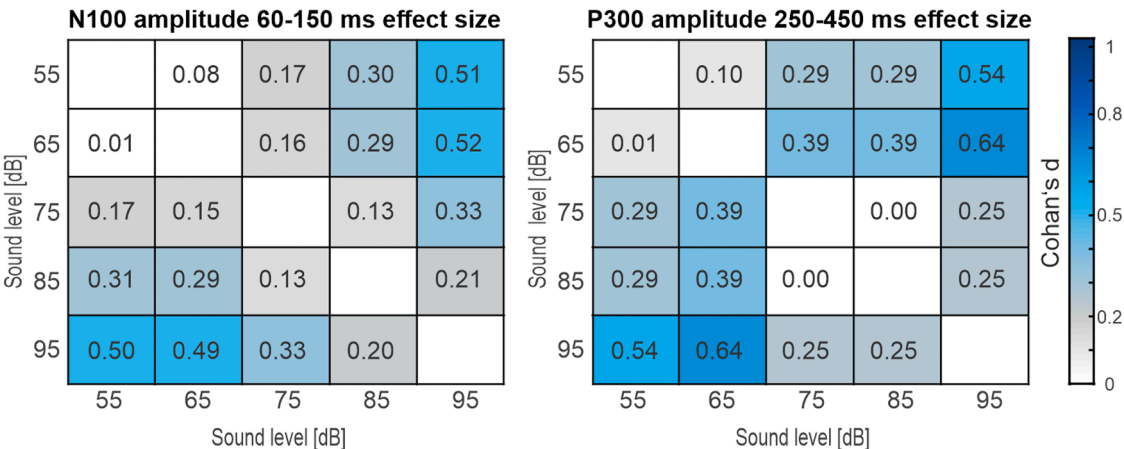


Fig. 5. Results for the effect size estimation employing Cohan's d for the N100 (left), and the P300 (right) potential in the sound level dependent analysis. An effect size of 0.5 is considered a medium effect. The effect size is indicated by the number in the respective fields.

3.1.3. P300 component (250 - 450 ms)

The amplitude plot of the P300 potential shows a non-linear increase in the amplitude (rainbow test $p = 0.03$) of the potential depending on the sound level (Fig. 3) (right). Again, a significant main effect of the sound level was found $F(4,1140) = 16.495; p < 0.001$, but again no significant result was found for the interaction between electrode position and sound level $F(32,1140) = 0.50; p = 0.99$. Subsequent post hoc t -tests resolving the main effect show a significant difference between the two lowest stimuli levels (55, 65 dB) and the three higher stimuli (75, 85, 95 dB) (Fig. 4). A similar picture is shown for the results of the effect size estimation (Fig. 5). The maximal effect is found for the comparison

between the 65 dB and 95 dB stimulus ($d = 0.65$), which indicates a medium effect size.

The estimation of the effect size between the 95 dB HL sound level and the other sound levels and between the 55 dB and the other sound levels revealed a medium value. Comparing the results for the N100 and P300 components, a linear relationship was observable between the amplitude and the sound pressure level for the N100 and a less pronounced increasing relationship for the P300 components. The amplitude of the P200 component shows no monotone dependency on the sound levels. Fig. 2(b) shows a topographic plot for the N100 and P300 potential, which illustrates the dependence of the amplitudes of both

potentials of the sound level.

3.2. Results for answer-dependent analysis

This section performs analysis dependent on the subjective feedback of the test subjects. To do so, the categorized (according to Fig. 1) subjective feedback of the participants is used to calculate a grand average according to their respective answers, locked to the sound onset. The results are shown in Fig. 6. Below the EEG signal, the rolling ANOVA analysis of the data is shown as described above. The time windows for the N100, P200, and P300 potentials are the same as for the sound-dependent analysis.

3.2.1. N100 component (60 - 150 ms)

Fig. 7 (left) shows the amplitude of the N100 potential against the categorized subjective loudness rating. The results of a two-way ANOVA for the mean amplitude over the N100 time window reveal a significant main effect of subjective loudness rating $F(6,1096) = 12.63$; $p < 0.001$. Similar to the sound level-dependent analysis, no significant result was found for the interaction between electrode position and subjective loudness rating $F(48,1096) = 0.26$; $p < 1.0$. The amplitude plot of the N100 component shows a linear dependency on the subjective loudness rating (rainbow test $p = 0.84$). However, contrary to the results from the sound level-dependent analysis, the data show that the amplitude for the two highest loudness categories is somewhat more distinct from the 5 lowest categories (A2-A6). This is also reflected in the post hoc t -tests (Fig. 8 (left)), where a highly significant difference is found when comparing the two highest categories (A7, A8) to the other categories (A2-A6) and between A6 and A2. A subsequent effect size estimation (Fig. 9) confirms this result.

3.2.2. P200 component (150 - 225 ms)

The analysis of the P200 amplitude shows a similar pattern as in the sound level-dependent analysis. The P200 amplitude drops off after a linear increase in the amplitude with increasing loudness rating (Fig. 7 (center)). In total, the P200 component exhibits a non-linear pattern (rainbow test $p = 0.02$). The results of the two-way ANOVA again reveal a significant main effect of subjective loudness ratings $F(6,1096) =$

12.77; $p = 0.001$ but no significant result for the interaction between electrode position and subjective loudness ratings $F(48,1096) = 0.55$; $p < 0.99$. The results of the post hoc t -test also show a similar picture as for the sound level-dependent analysis (Fig. 8 (center)). Here a highly significant difference ($p < 0.001$) was found between the answers A2 vs. A4, A2 vs. A5, A2 vs. A6, A3 vs. A5, A3 vs. A6, A6 vs. A7, and significant results ($p < 0.05$) for the comparisons between A5 vs. A7 A6 vs. A8. The absence of a continuous dependency from the subjectively lowest rated to the loudest sound level precludes the use of the P200 potential to discriminate subjective loudness perception.

3.2.3. P300 component (250 - 450 ms)

The amplitude of the P300 potential follows a small linear increase for the loudness ratings A2 to A6. However, for categories A7 and A8, the amplitude rises sharply (Fig. 7 (right)). The P300 amplitude therefore exhibits a non-linear relationship to the subjective loudness rating (rainbow test $p = 0.024$). The results of the two-way ANOVA again show a significant main effect of subjective loudness rating $F(6,1096) = 18.04$; $p < 0.001$ and no significant interaction between electrode position and subjective loudness rating $F(48,1096) = 0.34$; $p < 1.0$. The subsequent post hoc analysis (Fig. 8) shows a highly significant difference between the two loudest-rated categories and the rest. The effect size analysis shows a large effect of up to $d = 0.98$ (Fig. 9).

3.2.4. P300 single subject-level results

The EEG results of the single subject averages showed a similar behavior as the grand average data. However, the distinct amplitude increase for the P300 ERP is not present in all subjects. Some participants show a prominent P300 peak for the 95 dB HL and some even for the 85 dB HL sound level stimulus, whereas other subjects do not show a P300 component at all. The two groups of subjects differ in their subjective rating of the perceived loudness. For the subjects that rated some of the stimuli at the highest (A8) and second-highest (A7) categories, a P300 component was found for those answers. The data from subjects who did not rate stimuli with those ratings does not show a P300 potential. Fig. 10 (top) shows the averaged data for the Cz electrode for one subject that rated some stimuli in the loudest and second loudest categories. The right figure shows boxplots of the subjective loudness ratings

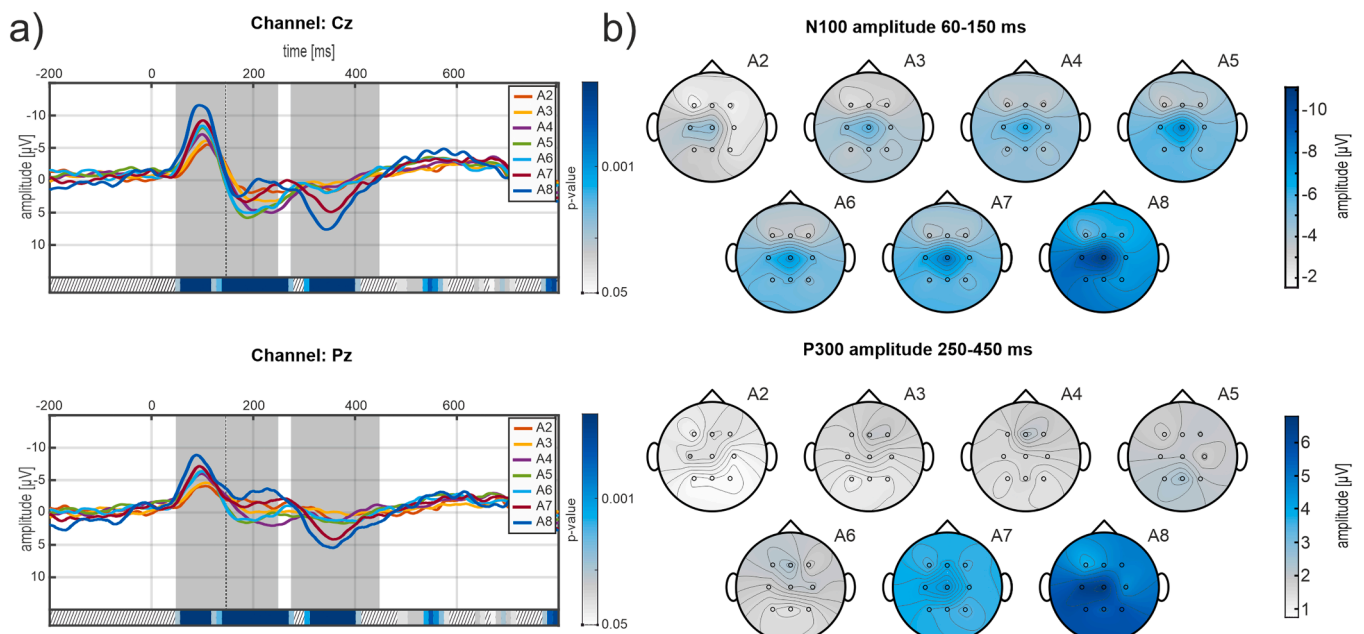


Fig. 6. Grand average of EEG data for subjective loudness answers at electrodes Cz and Pz (a). The rolling ANOVA is shown at the bottom of the ERP curves. In gray, the time windows for which the ANOVA regarding the N100, P200, and P300 potentials have been calculated are marked. Figure (b) shows the topographic maps of amplitude for the N100 and P300 potentials according to the segmented subjective answers. Negativity is plotted upwards.

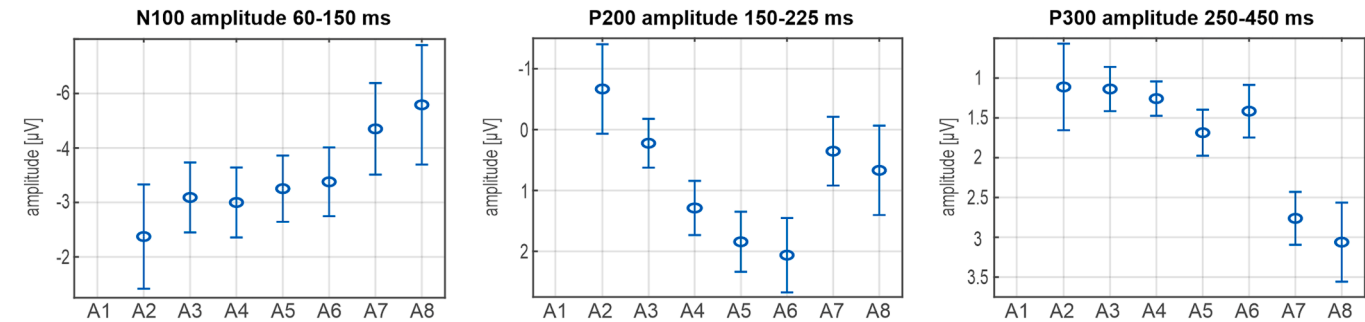


Fig. 7. ERP amplitude plots for the categorical subjective loudness rating merged over subjects for the N100 (left), P200 (center), and P300 (right) amplitude. The error bars indicate the 99% confidence interval. Negativity is plotted upwards.

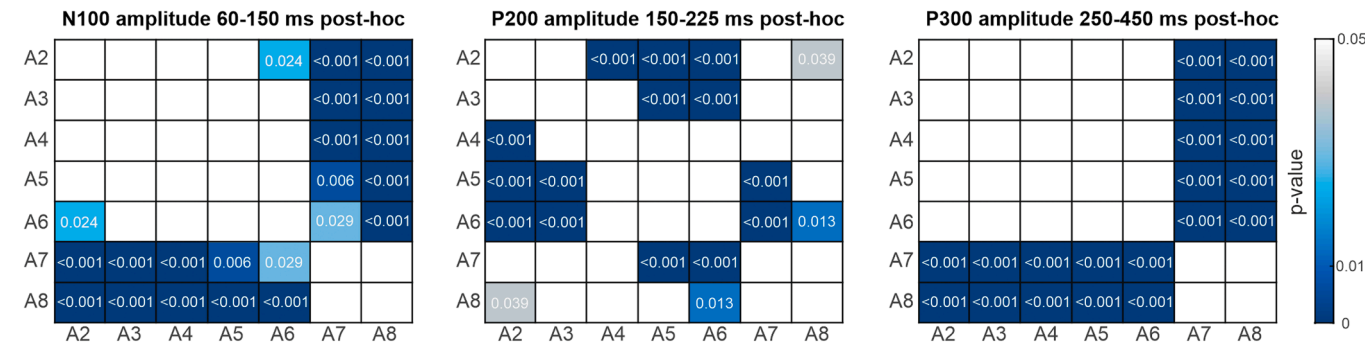


Fig. 8. Results for the post hoc t-test for the N100 (left), P200 (center), and P300 (right) potential with regard to the categorical subjective loudness rating. Statistically significant results are indicated by their p-values.

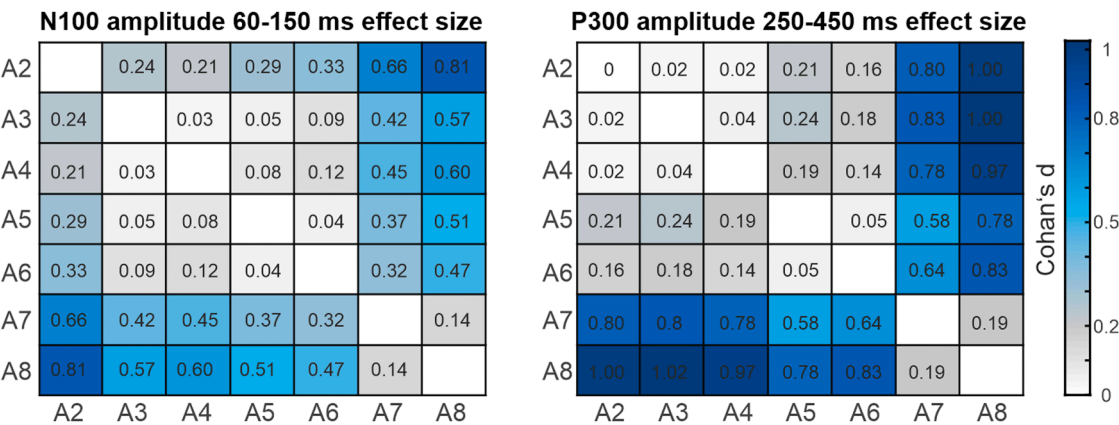


Fig. 9. Results for the effect size analysis using Cohan's d, for the N100 (left), P200 (center), and P300 (right) potential with regard to the categorical subjective loudness rating. The effect size is indicated by the number in the respective fields.

in response to the presented sound level of a stimulus. For this test subject, most of the 95 dB HL and some of the 85 dB HL stimuli have been rated as "too loud". A distinct P300 peak is visible for the loudest-rated stimulus in the averaged EEG signal. A running ANOVA analysis reveals a highly significant main effect for subjective loudness rating $F(6,56) = 28.98$; $p < 0.001$ for the P300 potential.

Figure 10 (bottom) shows the result for one subject that did not rate any stimulus by the two highest categories. This subject did not rate any stimulus higher than the third-highest loudness category ("loud"). The averaged results of the Cz electrode show no clear P300 component. The running ANOVA did not reach a significant result for this participant. For the P300 potential time window, as defined above, no statistically significant difference is found $F(4,40) = 1.42$; $p = 0.24$.

4. Discussion

In the present investigation, we have found a linear dependency of the amplitude of the N100 component and variations in the sound pressure level of an acoustic stimulus, as previously expounded in studies by (Mulert et al., 2005; Muñoz-Caracuel et al., 2021; Paiva et al., 2016). Notably, N100 potentials seem to be directly associated with the acoustic stimulus' physical attributes.

The results of the analysis of the P200 potentials are only partially consistent with the literature discussed. Here, analogous to the N100 potential, linear dependencies of the P200 amplitude with the sound level are observed (Barry et al., 2022; Billings et al., 2007; Legris et al., 2022; Mulert et al., 2005; Potter et al., 2017; Sugg and Polich, 1995). This can also be observed in our data. However, only up to a sound level of 85 dB or a subjective loudness rating between A2 to A6. At the higher

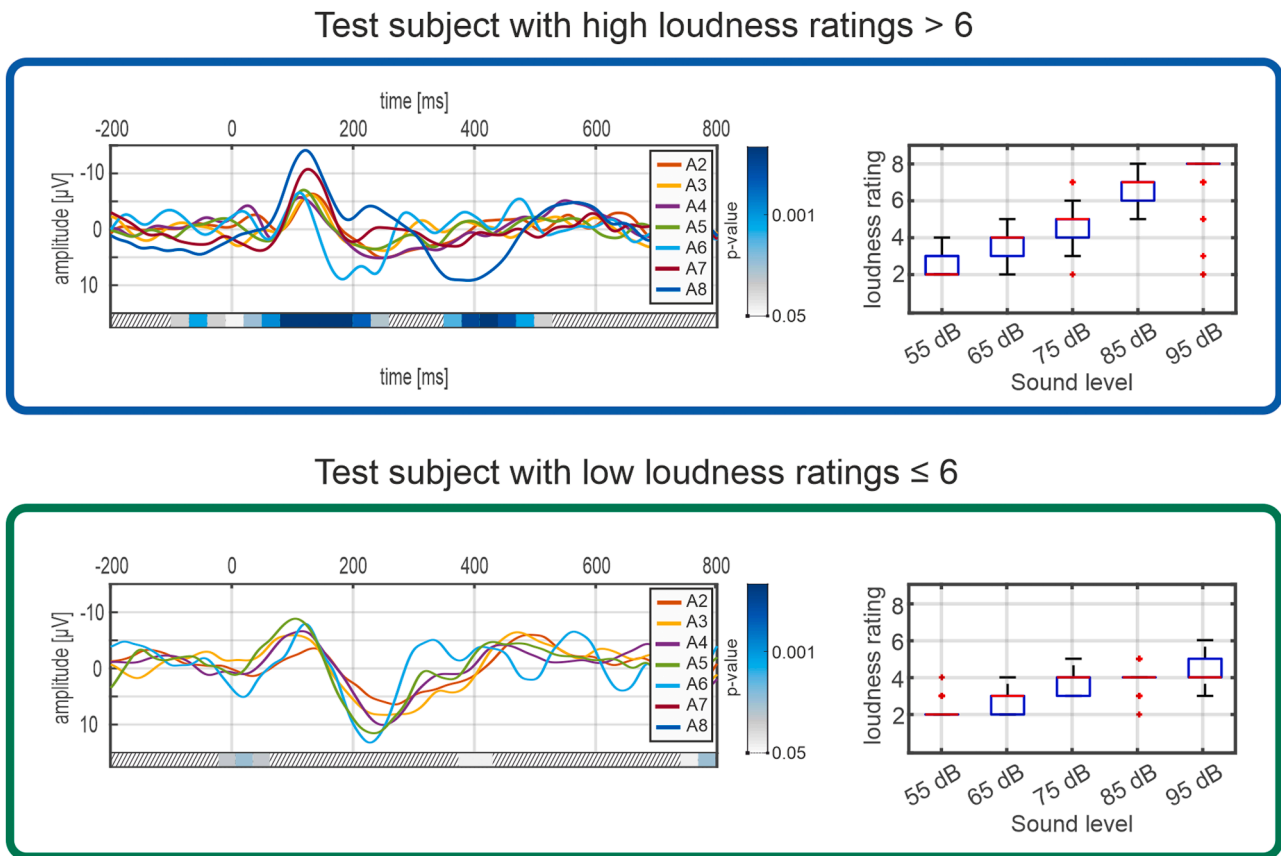


Fig. 10. EEG data for two exemplary subjects (left). The graph on the right shows a boxplot of the subjective loudness responses grouped by the sound level of the stimulus. The results of a subject with subjective loudness ratings above A6 (thus “too loud”) are shown in the top row, those of a subject with subjective loudness ratings below or equal A6 (thus max. “loud”) are depicted in the bottom row. None of the two subjects gave the response option A1 “too quiet”.

sound level (95 dB) or subjective loudness ratings (A7 and A8), a deviation of the linear dependency is observed. One reason for this behavior could be the overlap of the P200 component primarily associated with attention allocation, perceptual learning, and memory processes (Arnott et al., 2011) with a negative deflection such as an N200 component. N200 components were found to be associated with inhibition processes (Billings et al., 2007; Folstein and Petten, 2008; Sugg and Polich, 1995), which might come into play as a protection mechanism for too loud stimuli.

Conversely, our study has revealed a non-linear relationship between the amplitude of the P300 potential and the sound pressure. Specifically, we have observed a clear differentiation between reduced amplitudes of the P300 component for sound levels up to 65 dB and large amplitudes for the three highest sound levels. Considering P300 amplitude variations over all five sound pressure levels, a non-linear increase of the P300 amplitude emerges. Further, it is apparent that the amplitude of the P300 potential is not solely contingent on sound level but also exhibits a similar amplitude pattern with respect to the subjective perception of loudness. In our experimental context, this non-linear relation becomes evident exclusively for stimuli perceived as “very loud” or “too loud”, which indeed elicit a P300 component.

In the present study, the amplitude of the P300 potential did not follow the approximately linear dependency to the sound pressure level as shown by (Barry et al., 2022; Cass and Polich, 1997; Paiva et al., 2016; Sugg and Polich, 1995).

A reason for the discrepancy to the studies by (Barry et al., 2022; Cass and Polich, 1997; Muñoz-Caracuel et al., 2021; Paiva et al., 2016; Sugg and Polich, 1995) might be found in the differences in the acoustic stimuli, especially in the duration of the acoustic stimuli in use in our study. The psychoacoustic loudness perception depends on the physical

sound pressure and the stimulus duration (Buus et al., 1997; Stevens and Hall, 1966). Loudness perception relies on an integration process. The loudness time curve, the function of how loud a sound is perceived according to the stimulus duration, shows a plateau after around 250 ms, i. e., humans perceive the full loudness of a stimulus after about 250 ms. Shorter stimuli are, therefore, perceived as quieter at the same sound level. Paiva et al. (2016), for instance, used a 70 ms and 1000 Hz stimulus with the sound pressure level reaching up to 100 dB HL. They found linear increases in N100 and P200 amplitude with increasing sound levels in both averaged ERPs as well as at single-trial level, but no P300 component was elicited.

Mulert et al. (2005) used a longer stimulus of 200 ms at 1000 Hz at up to 100 dB; despite this, they did not report any effects on the P300 component. The study of Mulert et al. was performed in an MRI machine at a base sound level of 75 dB and a sound pressure level of max. 100 dB HL during the sequences. This background noise may be responsible for the lack of the effect. Adaptation effects can be suspected as the cause for the missing evidence of attention-drawing processes.

The P300 component can be interpreted as a marker of attentional mechanism to unexpected or significant events as described by (Debenet et al., 2005; Donchin, 1981; Goldstein et al., 2002). That might be an explanation for its appearance in our experiments. As discussed in Polich (2007), the P300 potential is sensitive to dishabituation processes. Such a process might appear when a stimulus that is experienced as too loud is presented in a series of similar auditory stimuli. This might happen under the present testing paradigm.

The correlation to the attention-drawing effect, reported by Dehais et al. (2019), as well as Giraudet et al. (2015), with the P300 ERP, confirms the hypothesis that the P300 wave might serve as a measure for alertness to a stimulus. Both papers reported a centro-parietal

distribution of the P300 potential. That, and the latency of above 400 ms, indicates the presence of a P3b potential as described in (Polich, 2007; Snyder and Hillyard, 1976), which is attributed to a conscious attention switch process. In contrast to that, the P300 potentials measured in the present study show a widespread distribution over frontal to parietal electrodes with a peak latency of about 350 ms. This indicates the concomitant occurrence of a P3a and P3b potential or as discussed by Barry et al. (2020), the measured component might fit their description of a novelty P300 (peak latency of 344 ms with a frontal to parietal distribution). The authors hypothesized that a novelty P300 component might indicate an orientating reflex that fits in our interpretation of an uncomfortably loud acoustic stimulus (Friedman et al., 2001).

Our study found that a significant P300 component is only present in subjects that did rate some stimuli as “very loud” or “too loud”. Our results show that the appearance of the P300 component coincides with the subjective loudness perception. As indicated by the two example subjects, we only found a P300 component in test subjects who perceived some stimuli as too loud.

The question naturally arises as to the reason for the appearance of the P300 component in this study. One assumption could be that the chosen experimental procedure shows characteristics of an oddball paradigm in which frequently presented standard stimuli are interspersed with rare target stimuli. This is based on the assumption that a rarely occurring very loud or too loud stimulus stands out against the frequent stimuli perceived as not too loud. Another explanation might be based on attention. Here, it is assumed that a very loud noise attracts a person’s attention. In practice, drawing a clear line between the two effects is difficult. Both effects likely play a role in this study.

A clinical application of this methodology pertains to the numerical distinction between EEG data associated with events occurring below and above the discomfort threshold. The outcomes of effect size analysis employing Cohen’s *d* suggest that these two categories exhibit discernible separability. Fig. 9 illustrates that the most pronounced divergence in amplitudes across all channels is evident in the EEG data corresponding to the two loudest responses.

However, only a modest effect size is observed when comparing the two loudest responses within themselves. This observation implies that the second-highest response category represents a combination of “loud” and “too loud” answers from the test subjects.

5. Conclusion

In this study, we found a non-linear relation between the presence of a P300 component and the subjective loudness perception in our test subjects. This relation might offer a tool to improve the treatment in patients with hearing aids and hearing implants by objectively identifying the uncomfortable loudness threshold.

The next step is to develop a tool to classify the EEG data into data sets below and above the uncomfortable threshold. For clinical application, such a method must ideally apply to single-trial measurements.

CRediT authorship contribution statement

Philipp Zelger: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Josef Seebacher:** Writing – review & editing, Conceptualization. **Simone Graf:** Writing – review & editing. **Sonja Rossi:** Writing – review & editing, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no competing financial interests.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2024.120796.

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