

Event-related potential correlates of consciousness in simple auditory hallucinations

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Tietoisuuden tutkimuskentällä *tietoisuuden hermostollisia korrelaatteja* (engl. neural correlates of consciousness, NCC) on tutkittu vuosikymmeniä. *Havaintotietoisuuden negatiivisuus* (engl. perceptual awareness negativity, PAN) ja *myöhäinen positiivisuus* (engl. late positivity, LP) ovat nykytutkimuksen valossa nousseet vankimmiksi ehdokkaiksi tietoisuuden hermostollisiksi korrelaateiksi. Vielä ei ole varmuutta tietoisuuden hermostollisista korrelaateista, mutta tutkimalla sisäsyntyisiä ärsykejä, kuten hallusinaatioita, ulkoisten sensoristen ärsykkeiden lisäksi voisi saada arvokasta lisätietoa tietoisuuden hermostollisesta pohjasta. Tässä tutkimuksessa tutkittiin *tapahtumasidonnaisten potentiaalien* (engl. event-related potential, ERP) avulla tietoisuuden hermostollisia korrelaatteja yksinkertaisissa kuuloaistin hallusinaatioissa. Tutkimuksen tavoitteena oli erityisesti selvittää, löytyvätkö *auditiivinen tietoisuusnegatiivisuus* (engl. auditory awareness negativity, AAN) ja myöhäinen positiivisuus hallusinaatiotilanteissa. Tutkimukseen osallistui 37 koehenkilöä Turun seudulta. Osallistujille esitettiin lähellä havaintokynnystä olevia piippausärsykejä, ja heidän tehtävänä oli arvioida kolmiportaisella *havaintotietoisuuden asteikolla* (engl. perceptual awareness scale, PAS) kuulivatko he piippauksen. Samanaikaisesti osallistujien tapahtumasidonnaisia potentiaaleja tutkittiin EEG-kuvauksen avulla. Tutkimuksessa havaittiin auditiivinen tietoisuusnegatiivisuus hallusinatorisissa tilanteissa, mutta myöhäistä positiivisuutta ei löytynyt hallusinatorista tilanteista. Auditiivinen tietoisuusnegatiivisuus havaittiin otsan ja keskialueen elektrodeissa 200–260 ms ärsykkeen ilmenemisen jälkeen. Tulokset tukevat auditiivisen tietoisuusnegatiivisuuden asemaa tietoisuuden hermostollisena korrelaattina. Jatkossa olisi mielenkiintoista tutkia hallusinaatioita myös muissa aistimodaliteeteissa.

Avainsanat: tietoisuus, auditiivinen tietoisuusnegatiivisuus, havaintotietoisuuden negatiivisuus, auditiiviset hallusinaatiot, elektroenkefalografia

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In the field of consciousness research, the neural correlates of consciousness (NCC) have been investigated for decades. Perceptual awareness negativity (PAN) and late positivity (LP) are emerging as the primary candidates for the NCCs, but it is still uncertain which one is true correlate. To address that, investigating states where stimulus is internal rather than external could provide insights and offer more information. In this study, we investigated event-related potential (ERP) correlates of consciousness in simple auditory hallucinations, specifically examining if auditory awareness negativity (AAN) or LP are present during hallucinatory trials. The research was conducted at the University of Turku with 37 participants recruited from the Turku area. Near-threshold beep stimuli were presented to the participants, and their task was to rate on a three-level perceptual awareness scale (PAS) if they heard the beep stimulus. EEG recording was used to measure the ERPs. In this study AAN was detected in hallucinatory trials, meanwhile LP was not present. AAN was detected between 200 ms and 260 ms after stimulus onset at frontal and central electrodes. These results support the idea of AAN being true neural correlate of consciousness. The recurrent processing theory gains support from these results, while these results question the global neural workspace theory. For future research, it would be interesting to explore hallucinations across other sensory modalities as well.

Keywords: consciousness, auditory awareness negativity, perceptual awareness negativity, auditory hallucinations, recurrent processing theory, global workspace theory, electroencephalography, awareness

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1. Introduction

Consciousness is defined as ‘internal knowledge or conviction; the state or fact of being mentally conscious or aware of something’ (Oxford English Dictionary, 2024), in other words, consciousness is everything you experience. All your feelings, memories, thoughts at any given moment and the individual’s awareness of themselves and their surroundings are part of consciousness. Even though consciousness is a vital and fundamental part of humanity, and it has been studied for decades, there is still no explanation for how and why any neural activity in the brain, or any physical process anywhere, can produce any kind of subjective experience. Even to this very day, there is no explanatory mechanism that mediates between neural activities and subjective experiences.

Through the study of consciousness and its neural processes, a comprehensive understanding of human minds could be achieved. A better understanding of consciousness could open many new doors in various scientific fields and result in breakthroughs among different branches of science. By understanding neural mechanisms behind consciousness, it would be possible to develop new medicine, treatments and implementations for illnesses that affect consciousness, such as coma, epilepsy, schizophrenia and Alzheimer’s disease. It would also be possible to solve many philosophical problems concerning humanity and human minds.

In neuroscience, the field of consciousness studies has been very active and scientists have tried to track down the neural correlates of consciousness (NCC) (Crick & Koch, 1990). The NCC are characterized as the minimal neural mechanisms that are together essential and sufficient for generating any conscious experience (Crick & Koch, 1990). One approach to identifying the NCC in situations where one is aware of a stimulus is to track down where and when sensory stimuli enter consciousness on the neural level. This area of consciousness research is known as studies on perceptual awareness. These studies contribute to identifying the NCC when one is aware of the stimulus, but they do not address other aspects of consciousness, such as presence and absence of consciousness, or emotions. The debate surrounding when and where sensory stimuli enter consciousness has led to various theories, primarily categorized into the early posterior theories and the late frontal theories.

In the category of late frontal theories, one of the most well-known theories is the global neural workspace theory (Dehaene et al., 1998). The global neural workspace theory suggests that a person becomes aware of stimulus when it is broadcasted to the global workspace, a distributed brain network, allowing different brain areas to process the information (Dehaene et al., 1998). According to this theory, consciousness is a result of globally broadcast, widespread processing of sensory information, and the prefrontal cortex has a key role in the global broadcasting of information (Mashour et al., 2020). On the neural level, the global workspace theory is connected to the P300 event-related potential (ERP) component. ERPs are changes in brain electrical activity, measured by EEG, that occur in response to specific events like the appearance of a stimulus or the performance of a motor action. P300 is a positive peak in ERPs and it is presented around 300-500ms after the stimulus (Dehaene & Changeux, 2011).

Among the theories in the early posterior category, recurrent processing theory (Lamme, 2006) is highly recognized. According to this theory, stimulus becomes conscious when the feedback loops in the brain amplify and stabilize neural representations of sensory input, making them accessible to conscious awareness. According to recurrent processing theory, the brain has different levels at which information is processed. Local recurrent processing is a stage where unattended stimulus is recurrently processed in sensory areas of the brain 150-300ms after stimulus onset, causing phenomenal consciousness (Lamme, 2018). Phenomenal consciousness is defined as the subjective experience of how it feels like to be in the world, such as vividness of colors and richness of sounds, which are often described as qualia. Without attention, the stimulus does not enter further than that and without further processes the stimulus cannot be reported. When attention is involved, it leads to deeper, global recurrent processing of the stimulus (Lamme, 2018). Global recurrent processing activates higher brain levels, including prefrontal and motor areas, approximately 300ms after stimulus, resulting in access consciousness (Storm et al., 2024). Access consciousness refers to the functional aspect of consciousness that enables information to be globally available for cognitive processes and it is often described as the spotlight of attention. Access consciousness allows mental content to be used by cognitive systems, supporting the ability to think about experiences in words and concepts, to voluntarily control actions, and to focus attention. As a result, it becomes possible to reflect on thoughts, engage in inner speech, and communicate experiences to others.

On the neural level, local recurrent processing leading to access consciousness and global recurrent processing resulting in phenomenal consciousness have been linked to different ERP components. The ERP component associated with recurrent processing is perceptual awareness negativity (PAN), whereas late positivity (LP) represents global recurrent processing (Storm et al., 2024). PAN and LP are both difference waves between aware and unaware conditions, with LP being a positive difference wave in the P300 time window (Eklund & Wiens, 2019; Koivisto & Revonsuo, 2010). The difference wave between aware and unaware conditions is calculated by subtracting the ERP of unaware trials from that of aware trials. This isolates neural activity specifically associated with conscious awareness by removing activity common to both conditions, thereby highlighting the brain processes unique to conscious perception and filtering out those related to unconscious processing or general sensory input. PAN is an ERP component that is characterized as negative deflection approximately 150-300ms after stimulus onset and it is located in primary sensory areas of the brain, depending on the type of sensory stimulus. PAN is a umbrella term for all sensory modalities, and its subcategories include visual awareness negativity (VAN), auditory awareness negativity (AAN) and somatosensory awareness negativity (SAN), all of which have similar temporal and functional characteristics (Dembski et al., 2021). The recurrent processing theory posits that PAN is proper neural correlate of consciousness (Dembski et al., 2021).

There are many divergencies between these two theories of consciousness, but one of the main differences is how they theoretically define consciousness. The global neural workspace theory posits that consciousness is solely characterized by access consciousness, which means that all conscious information is accessible for reporting and provoking voluntary movements. In contrast, the recurrent processing theory argues that besides access consciousness, there is also phenomenal consciousness, which can be described as 'being in the world' -experience. Phenomenal consciousness refers to the subjective feeling of particular experiences or mental states, such as the pain of a headache, the perception of the color red, or the taste of chocolate, which are often called qualia. The recurrent processing theory suggests that consciousness does not require attention, whereas the global neural workspace theory defines consciousness solely as attention-demanding access consciousness. According to the recurrent processing theory, phenomenal consciousness arises from local recurrent processing of the stimulus, while access consciousness requires additional processes in different brain areas, such as attention and working memory.

To confirm or deny these theories, empirical research needs to go beyond perceptual awareness. The findings of NCC studies are often influenced by sensory processing mechanisms when examining

perceptual awareness. However, by investigating states that represent consciousness in a purer form, in which sensory processing mechanisms related to external stimuli are not involved, such as dreams and hallucinations, we could uncover fundamental mechanisms of consciousness and deepen our understanding. Unfortunately, as far as we know, there have not been any studies that employ hallucinations, dreams, or other internally generated stimuli to investigate the NCCs. If studies of hallucinations or dreams show that PAN would remain present in the absence of LP when a person is aware of the stimulus, it would indicate that PAN is proper NCC and support the recurrent processing theory. However, if PAN won't be present, it would indicate that it might not be proper NCC which would point to other theories than recurrent processing theory. Additionally, it is also important to investigate the robustness of the NCC across different states.

The study aims to investigate whether the AAN can also be found in situations where sensory stimulus arises without external physical stimuli, and to the authors' knowledge, this has never been previously studied. One of such states would be auditory hallucinations, which we are investigating in this study. Hallucinations are sensory perceptions that appear real to the person experiencing them but occur without any external stimulus (Oxford English Dictionary, 2025). For example, a person might hear voices or see objects that are not actually present. Hallucinations and consciousness are closely linked, as hallucinations are a part of conscious experience. Unlike external physical stimuli, hallucinations arise internally, so they are not influenced by mechanisms that affect sensory information processing. This makes them a valuable tool for isolating the fundamental neural mechanisms underlying conscious experience and by studying them, we could gain more insight into which brain activations correlate with consciousness and are not connected to the processing of external sensory information. We predict that the internal hallucinatory sounds are perceived similarly to external physical stimuli, and thus AAN will be found in hallucinatory situations.

1.1 Components of the perceptual awareness negativity

1.1.1. Visual awareness negativity (VAN)

Among the different PAN components, VAN has received the most attention in research and the majority of evidence has strongly supported the hypothesis that VAN is a neural correlate of consciousness (Dembski et al., 2021). VAN is detected at posterior scalp electrode sites approximately 200ms after stimulus onset and its amplitude is notably stronger on the hemisphere opposite to the visual field where the stimulus appears (Förster et al., 2020). According to current understanding of mechanisms underlying consciousness, VAN reflects early recurrent processing of visual stimulus in lower visual areas, producing phenomenal consciousness (Koivisto & Revonsuo, 2010). In later stage of processing the information recurrent loops engage higher cortical areas, like fronto-parietal network, and this process results in access consciousness (Lamme, 2006) and can be pictured with LP (Koivisto & Grassini, 2016).

1.1.2. Auditory awareness negativity (AAN)

While VAN is already more widely recognized as a neural correlate of consciousness, its correspondent in the auditory field, AAN, has also started to be studied more extensively. AAN is a negative difference wave around 150-200ms after auditory stimulus at frontocentral, occipital or temporal electrodes, and it is followed by a positive difference wave, LP, about 300ms after stimulus at parietal electrodes (Dembski et al., 2021; Eklund & Wiens, 2019; Schlossmacher et al., 2021). The timing of AAN and LP can vary depending on the task and stimulus complexity (Filimonov, Krabbe, et al., 2024; Schlossmacher et al., 2021). More complex stimulus, like spoken language, can lead to prolonged AAN time window (Schlossmacher et al., 2021). AAN is located in bilateral auditory cortices, which are in superior temporal cortex (Eklund et al., 2019).

There is an ongoing debate about awareness and attention, particularly concerning whether attention is necessary for awareness or if the two can exist independently. On the visual field, plenty of studies support that awareness requires attention (Cohen et al., 2012; Koivisto et al., 2009), while many others suggest the opposite (Dehaene et al., 2006; Koivisto & Revonsuo, 2008; Lamme,

2003). In terms of ERPs, PAN is correlated with awareness, while LP is associated with attention (Förster et al., 2020; Koivisto et al., 2009). In the auditory domain there is limited research on this topic, but AAN appears to correlate with awareness while LP is influenced by feature based attention and response requirements (Filimonov, Krabbe, et al., 2024). Feature-based attention is a cognitive process that focuses on specific stimuli features, like color or shape, to efficiently process and respond to relevant targets while filtering out irrelevant information. Feature-based attention did not appear to affect AAN, but this result cannot be generalized to other forms of attention (Filimonov, Krabbe, et al., 2024).

In typical threshold tasks, such as in this study, subjects must report awareness by pressing a button for each trial and this requirement for manual response could interfere with the identification of NCCs. In the visual field, it has been found that VAN is not influenced by response requirements, but manual response has effect on LP (Koivisto & Grassini, 2016). The influence of response requirement has not been extensively studied in auditory field, though it seems that it does not impact AAN (Eklund et al., 2019; Filimonov, Krabbe, et al., 2024).

1.2. Hallucinations and consciousness

Hallucinations highlight the subjective nature of consciousness and offer a unique perspective for studying it. To identify proper NCCs, it is essential to isolate them from other factors that influence brain activity (Aru et al., 2012). Studying hallucinations introduces a novel approach to this field, as it helps to reduce the involvement of sensory processing mechanisms related to external stimulus. As far as we know, hallucinations have not previously been utilized in studies of NCC. However, this study investigates hallucinations, as studying them can provide more insight into consciousness than experiments using only physical stimuli to evoke sensations. Hallucinations represent pure consciousness and are not caused by physical stimuli, so they are not affected by the processes involved in the processing of physical stimuli.

Auditory hallucinations, which are the focus of this study, involve the perception of sounds, such as voices or tones, in the absence of corresponding auditory stimulus (Blom, 2015). Since hallucinations originate from the participants themselves, it is interesting to explore whether the AAN can be detected even in the absence of physical stimulus. In this study, unfortunately, the hallucinations were task-related and therefore not in their purest form. The study does not involve

stimulus-related activity, but it does have a clear task, and the hallucinations are not random, which limits the research. Nevertheless, it might be argued that the NCCs in simple auditory hallucinations are purer than in perceptual awareness.

1.3. Near-threshold stimuli

In studies on perceptual awareness, near-threshold stimuli are commonly used. In these studies (Doll et al., 2024; Filimonov et al., 2025; Koivisto & Grassini, 2016; Schlossmacher et al., 2021), stimuli are presented near each subject's awareness threshold, which is the point where the subject acknowledges the stimulus in roughly half of the trials. The purpose of using near-threshold stimuli is also to minimize variation in the stimulus and to vary it as little as possible (Förster et al., 2020). The "aware" stimulus is just above the threshold, while the "unaware" stimulus is just below it. This way, the physical stimulus changes as minimally as possible, while the aim is to generate differences only in the subjective awareness of the stimulus (Förster et al., 2020). By monitoring neural activity during these tasks, a comparative examination of the neural responses between trials identified as aware versus unaware reveals the neural correlate of consciousness. This study also employs this method. In this study, the near threshold stimulus is a beep sound that is barely strong enough to consciously perceived, meaning it is at or just below the absolute threshold. Aware-unaware trials in stimulus-present and stimulus-absent (hallucinatory) conditions will be analyzed separately.

2. Research questions

The aim of this study is to explore the NCCs in greater depth and assess their robustness across different states. By analyzing hallucinations, this study investigates whether AAN can be detected when sensory stimulus arises internally without external physical stimuli. The study enhances understanding of neural correlations of consciousness by identifying brain activations linked to conscious experience, independent of sensory processing of external stimuli.

The main research question in this study is: does AAN occur during simple auditory hallucinations? Simultaneously, we investigate the existence of AAN and LP in general, including stimulus-present trials, which we will investigate with the following question: do AAN and LP occur at all, including stimulus-present trials?

The main hypotheses are:

H1: AAN will be found in hallucinatory situations.

H2: AAN will also be found in stimulus-present trials.

H3: LP will also be observed, as access consciousness is required for subjects to report their sensations.

3. Methods

3.1. Participants

The study consisted of 37 participants recruited from the Turku area, all of whom were right-handed, had normal or corrected-to-normal vision and normal hearing, and didn't suffer from migraine, neurological or psychological diseases. Most participants were students from the University of Turku. The exclusion criteria were failure in calibrating individual auditory thresholds within 45%-65% of stimulus detection rate, absence of hallucinations, or noisy EEG data, meaning substantial noise over the majority of the electrodes before and after the preprocessing. EEG epochs were rejected when voltage exceeded $\pm 100 \mu\text{V}$ or contained muscle transients. Fourteen participants were excluded from the study: two had noisy EEG data, while eleven lack hallucinations (< 10 trials). The final sample size consisted of 23 participants (14 female, 9 male; $M = 24.2$ years, $SD = 3.6$, range 19–31).

3.2. Stimuli

A near-threshold beep stimuli (tone A, 440 Hz, 5 ms Hamming window) were presented using PsychoPy (version 3.0.7) (Peirce et al., 2019) on a Windows 10–based computer. The stimuli were played binaurally through in-ear earphones (Etymotic ER2 Tubal Insert Earphones, 10-ohm $\frac{1}{4}$ stereo). Before the actual experiment, participants performed a calibration procedure to find their individual awareness threshold. We determined each participant's 50 % detection threshold with a three-down/one-up adaptive staircase (step = 1 dB SPL; initial level = 25 dB SPL) using the same tone that later served as the near-threshold stimulus. The mean of the last six reversals defined the presentation level; silent catch trials were physically 0 dB SPL.

Responses were recorded with an Xbox gaming controller (model 1708). The participants' task was to rate on a three-level perceptual awareness scale (PAS) (Ramsøy & Overgaard, 2004; Sandberg & Overgaard, 2015) whether they heard the beep stimulus. The question was, "I heard the stimulus: X - not at all, A - weakly, or B - clearly." The participants pressed the blue (X), green (A) or red (B) trigger on an Xbox controller after every trial to report tone presence and selected one of the three PAS levels displayed on screen. Many previous studies examining AAN often use only two

response options which can lead to misclassifications of the awareness of the stimulus. For instance, subjects might label a faintly heard tone as "not heard". In contrast, using confidence ratings allows subjects to express how clearly they heard the stimulus, providing a more nuanced measure of awareness.

3.3. Procedure

The study consisted of six blocks, each with 25 near-threshold sounds and 75 stimulus-absent trials which were presented in a random order during the block, totaling 100 trials per block and 600 trials overall. The trial structure is presented in Figure 1. A fixation dot appeared in the center of the screen 500 ms before the beep stimulus, and participants were instructed to focus on it, conditioning the relationship between the predictive fixation dot and the sound occurrence. At block onset a 20-trial conditioning sequence of real tones reinforced this association and stimulus. The priming sequence of 20 trials did not account for the total amount of trials. The experimental blocks included 25 trials with the stimulus-present, and a sound was always played at a fixed interval after the dot, increasing the likelihood of hallucinations. The Pavlovian paradigm was used to trigger auditory hallucinations: before each block, a conditioning sequence of 20 consecutive sound trials was presented, and then the block started. For more detailed information about the procedure, refer to the article by Filimonov et al. (2025), which is based on similar data as this thesis.

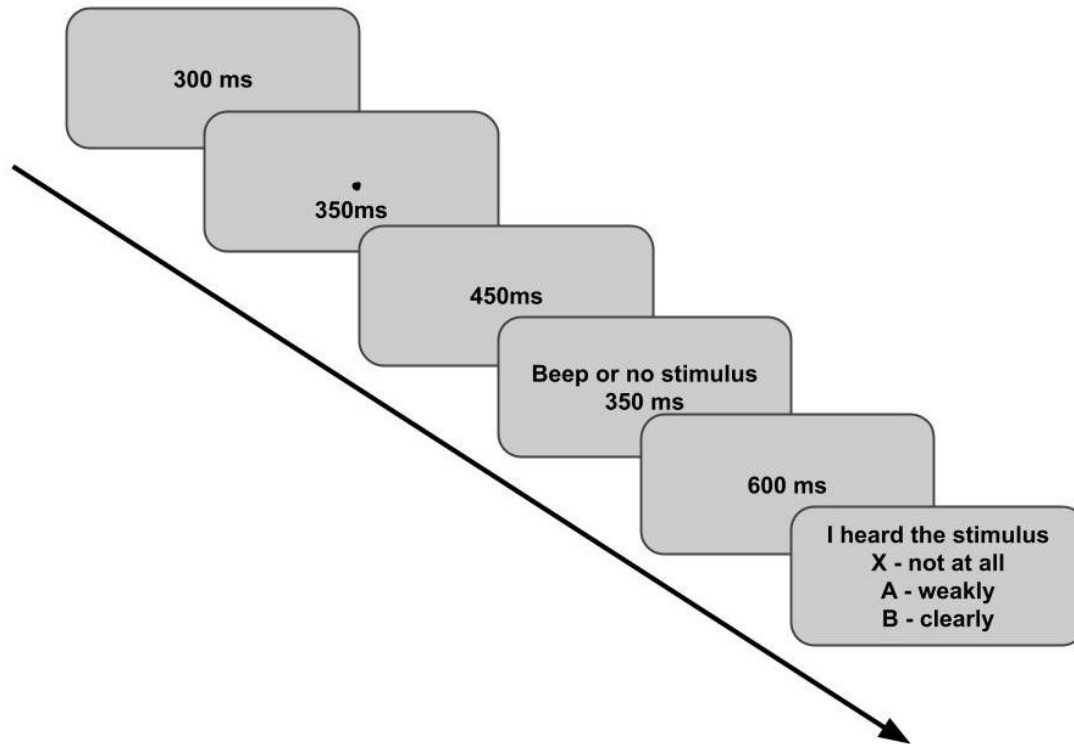


Figure 1. Trial structure.

3.4. Operationalization of hallucinations

In this study, hallucinations were operationalized as follows: if the stimulus was absent but the participant reported hearing it as either ‘weakly’ or ‘clearly’ on the PAS scale, the response was classified as a hallucination. When the stimulus was present and the participant responded ‘weakly’ or ‘clearly’, the trial was categorized as aware. If the participant answered ‘not at all’, regardless of whether the stimulus was absent or present, the response was classified as not heard.

3.5. EEG recording

The EEG data was recorded using active 64 Ag/AgCl sintered ring electrodes attached to a recording cap (EASYCAP GmbH, Germany) and NeurOne (Mega Electronics Ltd) amplifier using a band pass of 0.05–100 Hz, with 500 Hz sampling rate. The EEG was recorded using the Fz electrode as a reference and later converted to a common average reference during the preprocessing stage.

3.6. EEG data analysis

The EEG data was processed using EEGLAB (Delorme & Makeig, 2004) (version, 2024.0) and Matlab (version, R2022b). The preprocessing pipeline began with automated bad channel detection using EEGLAB's 'pop_rejchan' function, employing kurtosis, joint probability, and spectral criteria at a 4 standard deviation threshold. A 0.5 Hz high-pass filter (FIR, Hamming windowed; transition bandwidth, 1 Hz; filter order, 1650) was subsequently applied following current ERP optimization guidelines (Zhang et al., 2024), after which remaining noisy channels were removed through visual inspection. Line noise at 50 Hz was moderated using EEG lab function 'pop_cleanline', and continuous data were low-pass filtered at 30 Hz (FIR, Hamming windowed; transition bandwidth, 6.7 Hz; filter order, 247) before epoching. The count of excluded electrodes varied from 5 to 13 across participants. Independent components identified as artifactual through the ICLabel plugin (Pion-Tonachini et al., 2019) (version 1.4.) were rejected based on concurrent noise signatures in scalp topography, power spectrum, and trial-to-trial variability. Spatially interpolated electrodes were reconstructed using EEGLAB's spherical interpolation function 'pop_interp'. Finally, data was baseline-corrected (-200 to 0ms relative to stimulus/blank onset) and re-referenced to linked mastoids.

ERP data were further analyzed with Matlab (version, R2022b) software. The three-level PAS scale was reduced to two levels for data analysis. The levels 'clearly' and 'weakly' were combined into a single category, 'aware', while 'not at all' was placed in the 'unaware' category. We implemented an Amplitude ~ Awareness + (1|id) linear mixed-effects model with Awareness as fixed effect and random intercept as a random effect separately for stimulus-present and stimulus-absent (hallucinatory) trials. In order to model AAN, we analyzed a mean amplitude in predefined 200 - 300 ms time window and electrode cluster, which included 'Cz', 'Pz', 'Fz', 'F1', 'F2', 'FC1', 'FC2', 'C1', 'C2', 'CPz', 'CP1', 'CP2', 'C3', 'C4', 'FC3', 'FC4', 'F3', 'F4', 'CP3', 'CP4' electrodes, that are commonly reported in AAN studies (Dembski et al., 2021; Eklund et al., 2019, 2020; Filimonov et al., 2024, 2024). For LP, the predefined time window was 300 - 700 ms and electrode cluster included 'Fp1', 'FPz', 'Fp2', 'AF3', 'AF4', 'F5', 'F6', 'F3', 'F1', 'Fz', 'F2', 'F4', 'FC5', 'FC3', 'FC1', 'FC2', 'FC4', 'FC6', 'C5', 'C3', 'C1', 'Cz', 'C2', 'C4', 'C6', 'CP5', 'CP3', 'CP1', 'CPz', 'CP2', 'CP4', 'CP6', 'P5', 'P3', 'P1', 'Pz', 'P2', 'P4', 'P6', 'PO3', 'POz', and 'PO4' electrodes (Eklund et al., 2019, 2020)

3.7. Ethical considerations of the research

This study was accepted by the Ethics Committee for Human Sciences at the University of Turku. All the participants were voluntarily participating, and they gave their informed consent in accordance with the Declaration of Helsinki before participating.

4. Results

The number of hallucinatory experiences varied widely between individuals. The amount of aware and hallucinatory trials per participant are presented in Figure 2. Participants experienced between 12 and 220 ($M = 90.91$, $SD = 69.87$) hallucinatory trials individually, whereas the number of aware trials with sound ranged from 27 to 147 ($M = 95.65$, $SD = 37.35$).

ERPs were calculated for 23 participants. Grand averages from Fz electrode are represented in Figure 3. Scalp topographies for stimulus-present and hallucinatory conditions show aware–unaware differences in Figure 4. The results of the scalp topographies of the different conditions in Figure 4 show mainly negative awareness-related ERP over frontal and central regions in the AAN time window of ~ 200 ms and onward.

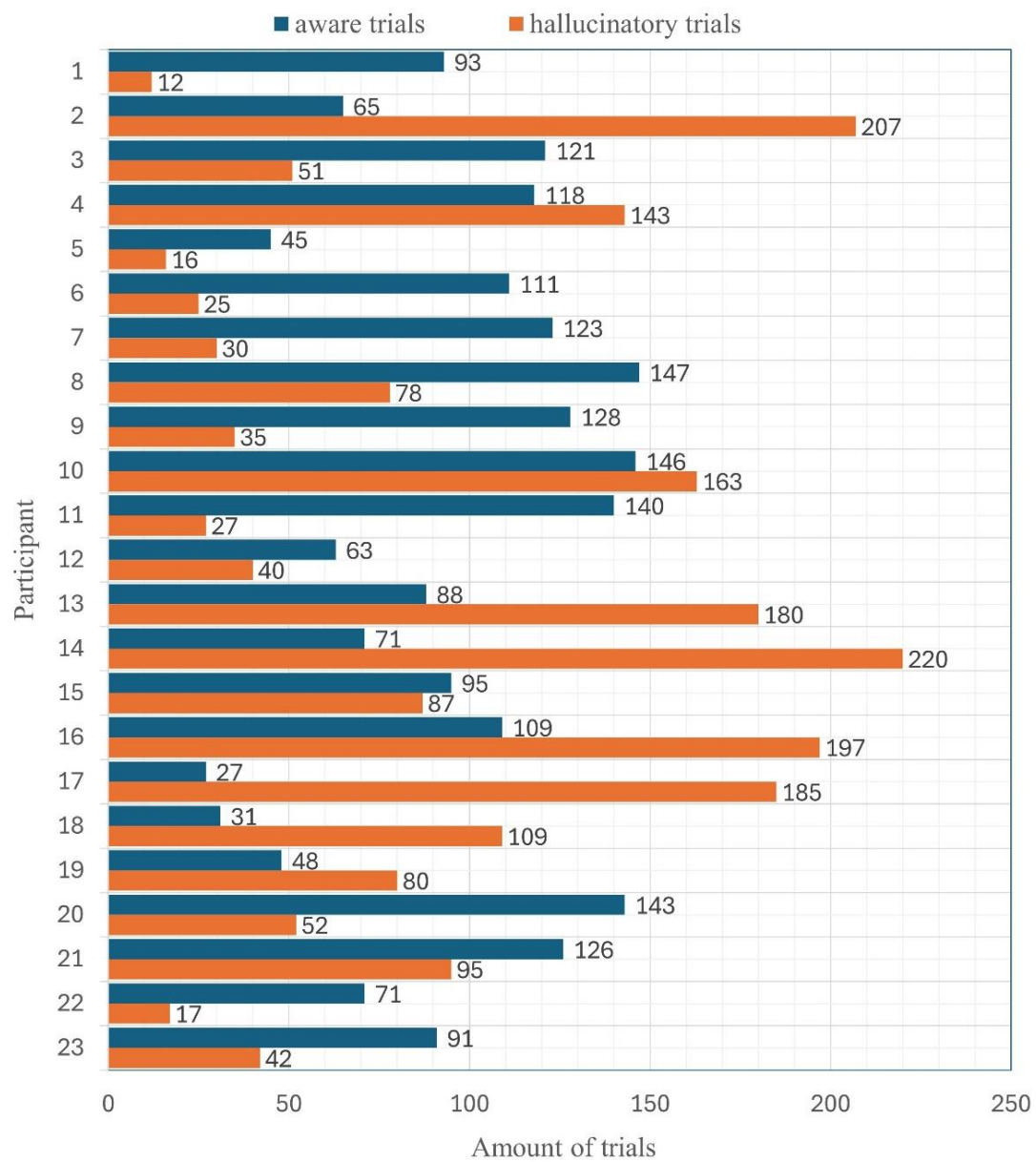


Figure 2. The amount of aware and hallucinatory trials per participant.

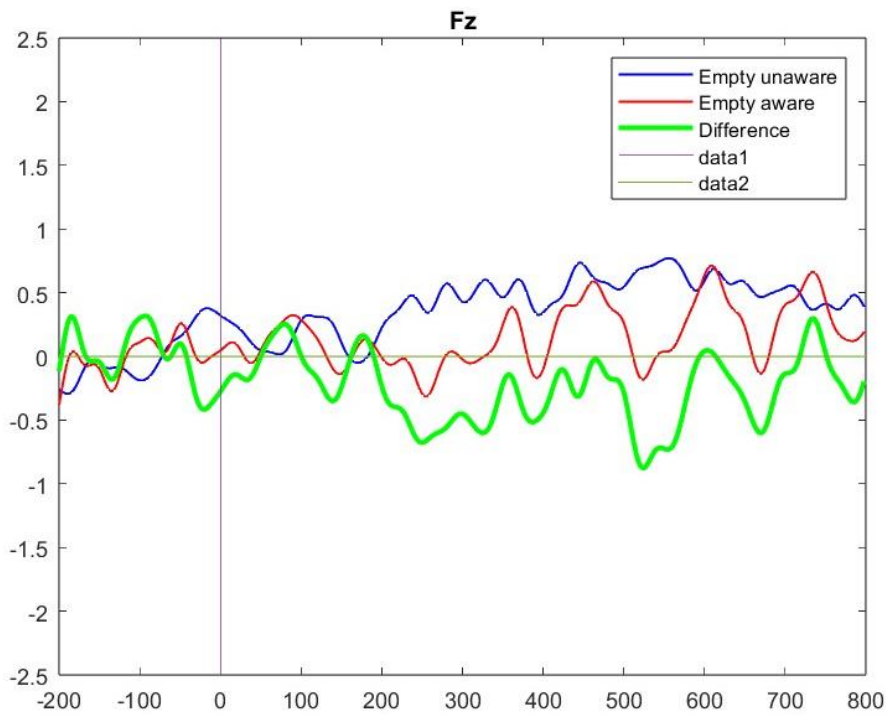


Figure 3. ERP amplitudes of aware (hallucinatory) and unaware trials over the Fz electrode.

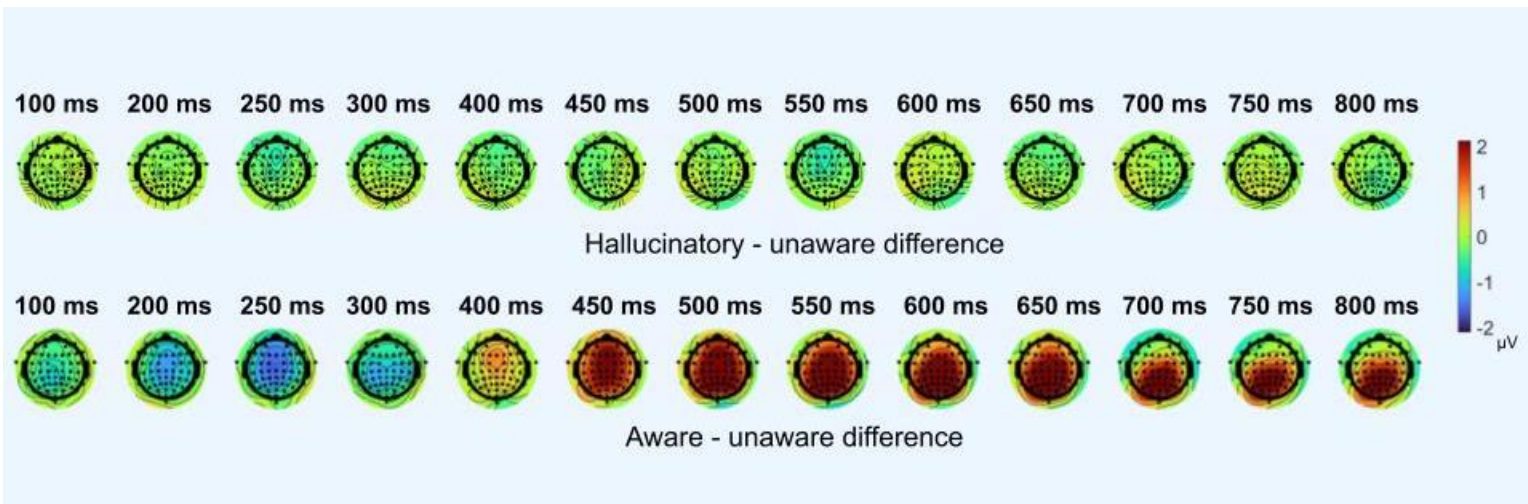


Figure 4. Scalp topographical plots of the aware-unaware difference waves in stimulus-present and hallucinatory conditions.

The linear mixed-effects model in the AAN time window showed significant effect of awareness in both hallucinatory, $SE = 0.157$, $t(10347) = -2.05$, $p = .04$, 95 % CI [-0.63, -0.01] and stimulus-present trials, $SE = 0.214$, $t(3448) = -5.76$, $p < 0.001$, 95 % CI [-1.65, -0.81]. The linear mixed-effects model in the LP time window showed significant effect of awareness in stimulus-present trials, $SE = 0.161$, $t(3448) = -6.12$, $p < 0.001$, 95 % CI [-1.30, -0.67], but not in hallucinatory trials, $SE = 0.102$, $t(10347) = -1.22$, $p = .22$, 95 % CI [-0.32, 0.08].

The variance attributed to subject-level differences was negligible in both hallucinatory ($\sigma \approx 6.0163 \mu V$) and stimulus-present trials ($\sigma \approx 6.71 \times 10^{-16} \mu V$), suggesting that variability was at the trial level.

5. Discussion

The aim of this study was to investigate the NCCs of auditory consciousness more thoroughly and evaluate their consistency across various states. By examining hallucinations, the study sought to determine if AAN can be detected when sensory stimuli originate internally. AAN was detected between 200 ms and 300 ms after stimulus onset at frontal and central electrodes (Filimonov et al., 2025), while LP was not present. The scalp distribution of AAN aligned with findings from previous research that used linked mastoids as a reference, with AAN appearing over frontal, central and parietal areas (Filimonov et al., 2022, 2025; Filimonov, Krabbe, et al., 2024; Filimonov, Tanskanen, et al., 2024).

We investigated whether AAN occurs during simple auditory hallucinations, with the main hypothesis being that AAN would be present during these hallucinations. The results align with the main hypothesis that AAN occurs during simple auditory hallucinations. Additionally, we hypothesized that AAN would be present in stimulus-present trials, and the results further support this prediction, as AAN was also detected in stimulus-present trials. Another hypothesis was that LP would be observed in both hallucinatory and stimulus-present trials. This hypothesis received partial support, as LP was significant in stimulus-present trials, but not in hallucinatory trials.

The reason LP was not present in hallucinatory trials might be explained by its role in covert processes. LP is associated with access consciousness (Koivisto & Grassini, 2016), higher-level stimulus processing (Filimonov, Tanskanen, et al., 2024), attention (Filimonov, Tanskanen, et al., 2024; Koivisto & Revonsuo, 2010), and response requirements (Filimonov, Krabbe, et al., 2024), which are linked to the processing of external stimuli. Since hallucinations occur without external stimulus, this may explain the absence of LP. LP typically follows PAN during aware task-relevant or attended stimuli, acting as a neural correlate for the integration of conscious content into higher cognitive processes. For example, in a study of feature-based attention and auditory consciousness (Filimonov, Krabbe, et al., 2024), it was found that AAN correlated with awareness, while LP was influenced by feature-based attention. This indicates that when a physical stimulus was presented, LP correlated with the analysis of the stimulus and its features. However, in hallucinatory trials, there was no external stimulus processing for LP to correlate with. Another possibility is that LP was not detected due to changes in neural implementations during hallucinatory trials, despite the function of LP remaining unchanged.

AAN was present in both hallucinatory and aware trials, but it was significantly stronger in aware trials compared to hallucinatory trials. This difference is likely due to the presence of physical stimulus in aware trials. Even though the stimulus was very weak and close to the threshold, it could still have produced stronger and more vivid neural responses than hallucinations. The level of perceptual clarity may have differed between the conditions, which is consistent with the level of processing hypothesis (Filimonov, Krabbe, et al., 2024; Jimenez et al., 2018). According to the level of processing hypothesis, conscious stimulus perception can be divided into low-level stimuli, which include features such as the color of an object, and high-level stimuli, which include letters, words, and meanings (Jimenez et al., 2018, 2021). Levels of awareness can also vary, and research in the field of visual consciousness has shown that increased awareness of low-level stimuli is associated with stronger VAN (Jimenez et al., 2021). This effect may also have occurred in this study, as we used low-level stimuli.

The recurrent processing theory gains support from this study, as the AAN was detected in hallucinatory trials, suggesting that it is proper NCC. These findings also question the global neural workspace theory, which does not recognize phenomenal consciousness and relies solely on access consciousness, proposing that LP is proper NCC. However, LP was not present in hallucinatory trials in this study, challenging the theory's claim that LP is the proper NCC. Given that hallucinations are internally generated conscious phenomena, the presence of AAN and the absence of LP in hallucinatory trials suggest that the AAN is proper NCC of auditory awareness.

5.1. Strengths of this study

The three-level PAS (Sandberg & Overgaard, 2015) was used in this study, as it appears to reflect conscious awareness more accurately than forced-choice responses. We also employed Pavlovian conditioning to evoke hallucinations, which may have contributed to the low false alarm rate observed in this study. We also had a reasonable number of participants in this study (n=23), although it would have been beneficial to have more. Furthermore, motor preparation was unlikely to influence the results, as participants were required to press a button on every trial, including those in which they were unaware of the stimulus.

5.2. Limitations and future research

While our study advances the investigation of consciousness by examining hallucinations that are not triggered by external stimuli, it is important to acknowledge the limitations of this experimental design. The hallucinations remain task-related rather than random, even though they are purer in terms of consciousness than perceptual awareness. It could also be argued that in our study, high stimulus expectations were responsible for the hallucinations. However, the cause of the hallucinations is not relevant, as our focus was not on investigating their origin, but rather the hallucinations themselves.

This study is pioneering and represents a significant step forward in the field, but further research is needed to replicate the results and to gain more insight into consciousness. Extending these investigations to other sensory modalities besides hearing could help reveal whether research on sensory or visual hallucinations leads to similar outcomes. This study is a step forward in understanding the nature of consciousness, but more research is needed to make broader assumptions.

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