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The role of attention and response requirements on ERP correlates of auditory awareness

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Previous research on electrophysiological correlates of auditory awareness has found both an early “auditory awareness negativity” (AAN) and late, “late positivity” (LP) as potential markers of auditory awareness. Earlier studies have sought to separate correlates of auditory awareness from response requirements but have come up with mixed results. Furthermore, no previous studies have investigated the effects of attention on the recently discovered correlates of auditory awareness. We implemented a GO / NOGO paradigm to control for both attention and response requirements, whilst measuring the effects of the latter on previously discovered correlates of auditory awareness AAN and LP using a factorial mass univariate approach. The results show a prolonged AAN for aware trials starting around 250 ms post stimulus, a relatively late LP in 450 - 600 ms post stimulus when the interaction of response requirements was factored in with awareness, a mid-latency LP for awareness and response requirement interaction around 500 ms and a late LP starting from 700 ms post stimulus related to response requirements and attention but not awareness. Given the two-part structure of the LP component, the result seems to corroborate earlier studies suggesting the earlier part of LP is domain – specific, while the later part is domain-general. The scalp topography of AAN was left lateralised possibly because the stimuli were syllables. We also found a negativity after around 400 ms after stimulus onset, which could be the language-related N400 component. The results are in line with theories that regard the AAN as the earliest correlate of auditory awareness and LP as later correlate of access consciousness. The early AAN was not affected by attention, while the later LP showed modulation by both attention and response requirements.

Keywords: Auditory awareness, Attention, Response requirements, ERP, Cognitive Neuroscience, Consciousness, mass univariate analysis.

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1 Introduction

1.1 Concepts of consciousness and empirical theories of consciousness

Over two decades have passed since the search for the neural correlates of consciousness (NCC) started in earnest in the beginning of the 1990s when (Crick & Koch, 1990) introduced the first empirical theory of consciousness combining both psychology and neurobiology. The NCC are defined as the minimal neuronal mechanisms jointly sufficient for any one specific conscious percept (Chalmers, 2000; Koch, 2004). Since visual input is highly structured and relatively easy to control, the visual modality has been extensively used as an analogue for explaining how conscious experiences can arise from underlying neural processes (Crick & Koch, 1998). Recent developments have also been made in studies trying to find the neural correlates of auditory awareness (Eklund & Wiens, 2019) and multimodal awareness as well (Filimonov et al., 2022).

Research into the NCC of consciousness usually makes a distinction between consciousness as a state and specific contents of consciousness. When referring to consciousness as a state, it is taken to be equivalent to wakefulness or responsiveness. When referring to contents of consciousness, the focus lies on the sensory-based content, as well as our thoughts and emotions that can be subjectively experienced. Studies into the contents of consciousness often contrast brain activity related to a particular stimulus with brain activity when the stimulus is absent (Koch et al., 2016). According to some authors, contents of consciousness can further be divided into whether they are simply experienced subjectively “phenomenal consciousness” or can be accessed for further cognitive manipulation “access” or “reflective consciousness” (Block, 1995; Revonsuo, 2009).

Different empirical theories that try to explain how and where in the brain consciousness is manifested are based on different definitions of consciousness, which has led to an ongoing debate between proponents of so-called “early” vs “late” correlates of consciousness. Theories of consciousness such as recurrent processing theory (RPT) acknowledge a distinction between phenomenal consciousness and access or reflective consciousness (Lamme, 2000). According to RPT unconscious detection of different visual features, changes to become phenomenally conscious as result of recurrent processing in the visual cortex at around 100 ms post-stimulus (Lamme, 2000). According to the contrasting view held by proponents of the global neuronal workspace theory (GNWT), activity in the visual cortex is

regarded as preconscious. Only when a stimulus is selected for further processing in a global neuronal workspace, involving higher order cognitive functions in the fronto-parietal areas can it be deemed conscious. The theory also regards top-down attentional modulation as necessary, although not sufficient, for conscious perception (Dehaene & Naccache, 2001).

1.2 Electrophysiological correlates of awareness

The use of electroencephalography and event-related potentials (ERP) is a common method to investigate cognitive processes that happen on a short time scale (Luck, 2014). Since processes related to both attention and awareness happen on a millisecond (ms) time scale, ERP analysis is a good tool for studying how they relate to auditory sensory perception. Different components are usually grouped together if they occur in the same latency range and have the same deflection pattern. The first positively deflecting waveform is called the P1 and peaks at about 50 ms post-stimulus and the first negative deflecting waveform is called N1, peaking at about 100 ms post-stimulus (Luck, 2014).

Research into visual awareness has revealed two potential ERP correlates: the first one appears during the N1-N2 time window and is called the visual awareness negativity (VAN), the second one appears in the P3 range and is labelled as the late positivity (LP) (Koivisto & Revonsuo, 2010). A similar two -component arrangement has also been found in the auditory domain, the auditory awareness negativity (AAN) occurring in the N2 range and the LP appearing in the P3 range (Eklund & Wiens, 2019). An earlier MEG study also observed an awareness-related negativity appearing at 50 - 250 ms post-stimulus at the bilateral auditory cortices (Gutschalk et al., 2008). Later source localization models indicate that the neural sources of AAN are located in the bilateral auditory cortices in the superior temporal cortex and the LP in the ventral temporal cortex as well as ventral prefrontal cortex (Eklund & Wiens, 2019). To isolate awareness – related effects from other ERP components related to basic sensory and perceptual processes, amplitudes between unaware and aware conditions are contrasted. The resulting amplitude difference (or difference wave) between the conditions are the AAN / VAN and LP components (Förster et al., 2020).

A recent study on both auditory and visual correlates of awareness found evidence for a modality-specific NCC of awareness between 200-300 ms (AAN, VAN). The later LP component contained different features, with the early part being more modality-specific and late part being more modality-general (Filimonov et al., 2022). Reviewing visual, auditory as well as somatosensory EEG and MEG correlates of awareness, Dembski et al., (2021)

suggested an umbrella-term for the awareness negativity component family, “General Perceptual Awareness Negativity” (PAN), found in all three modalities. The PAN is composed of VAN, AAN and a negative-going somatosensory-evoked potential (SAN), that has a peak latency of ca 120-180 ms (Auksztulewicz et al., 2012).

In summary, ERP components correlating with awareness in both visual and auditory modalities have been found to occur both in early and late phases of perceptual information processing. Recent studies seem to suggest that LP contains both modality specific and modality general features, while both AAN and VAN seem to be modality-specific. There is also evidence for an early negative going awareness component in the somatosensory modality SAN, which has led to the suggestion of an umbrella-term the “General Perceptual Awareness Negativity” (PAN) for all the negative going components. Theories, such as RPT (Lamme, 2000) suggesting that awareness occurs in early stages of sensory processing also state that the earlier components VAN and AAN are the true neural correlates of consciousness, while theories suggesting that awareness occurs later, such as GNWT, state that LP is a true NCC (Dehaene & Naccache, 2001).

1.3 Separating awareness from other possible confounds

An important aspect in the search for NCC is to isolate the NCC “proper” from other confounding perceptual and cognitive processes related to e.g., attention and response requirements that might occur both before or after the real NCC (Aru et al., 2012). An exhaustive account of how said confounds affect the correlates of awareness is out of the scope of the present thesis. However, depending on the experimental paradigm, studies have found that both the VAN and LP components of visual awareness can vary in both amplitude and latency (for a recent review on the subject see Förster et al., 2020).

In an attempt to dissociate response selection from auditory awareness (Eklund et al., 2019) used a tone detection task while manipulating the response requirements of reporting awareness. The experiment consisted of two conditions, one where subjects manually reported their awareness and another where they reported if they did not detect a tone, i.e., were not aware of the tone. Contrary to findings in the visual domain, where LP has been found to vary depending on response requirements (Koivisto et al., 2016) the authors found that both AAN and LP were unaffected by response requirements (Eklund et al., 2019).

On the other hand, Schlossmacher et al., (2021) reported that the LP was present only during task relevant stimuli which required participants to respond. Instead of a mid-latency LP they observed a sustained AAN in the same time window. However, the authors used a more complex auditory stimulus (words instead of beeps), which could have led to an extended AAN but also a late LP for task relevant stimuli (Schlossmacher et al., 2021). In a similar vein, Ye and Lyu, (2019) also found VAN to be unaffected by task manipulation. The authors asked participants to either directly report if they detected a stimulus or delay their answer. Apart from VAN being unaffected by the task manipulation LP was found to vary depending on the task, which led the authors to suggest LP could be an index of post-perceptual processes such as working memory or perceptual decision making rather than awareness (Ye & Lyu, 2019).

Together these studies seem to show mixed and inconclusive results regarding AAN and VAN. Similarly, how much LP is affected seems to depend on the modality in question as well as the stimulus being used, with the results pointing to some form of effect on the LP component in both the visual and auditory modality.

Another highly debated issue is whether attention is a prerequisite for awareness and vice versa. What complicates the matter is that attention like awareness is a multifaceted concept. A first distinction is usually made between whether attention is exerted voluntarily or whether something catches the attention. The former is referred to as voluntary or endogenous attention and is driven by top-down processes, while the latter is referred to as exogenous or stimulus driven (Marinato & Baldauf, 2019).

According to early models of attention in cognitive psychology attention was seen as having a limited capacity capable of performing only one task at a time. The limited capacity was thought to result in an attentional bottleneck at a fixed location somewhere along the auditory processing pathway, after which only attended stimuli are processed further. This in turn led to different structural models of attention that placed the bottleneck at an either early or late stage of auditory processing (Giard, 2000). According to the early -selection model, attentional modulation can occur before stimuli can be fully processed (Treisman & Riley, 1969). The late- selection model holds that attention only enters the stage after stimuli have been fully processed, thereby only controlling which stimuli become accessible for consciousness, memory and response (Deutsch & Deutsch, 1963). Later research,

however, seems to suggest that attention operates at both early and late stages of perceptual processing depending on e.g., stimulus and task parameters (Vogel et al., 2005).

With regards to ERPs related to auditory attention, a series of studies have found evidence for attentional modulation of difficult-to-detect targets as early as 20-50 ms after stimulus onset, during the P20 and P50 waves (Woldorff et al., 1993; Woldorff & Hillyard, 1991). These early attentional effects are difficult to measure since the early ERP components are small and usually require highly focused attention in order to be influenced; a later effect in the N1 range (ca 100 ms) measured over fronto-central electrodes is therefore most commonly observed in relation to auditory attentional modulation (Luck & Kappenman, 2011). The resulting difference wave (Nd) from subtracting the N1 wave of attended stimuli from the N1 wave of non-attended stimuli, has been dubbed by some authors as the processing negativity (PN) (Näätänen et al., 1978). The later P3 component appearing around 250-500 ms has also been linked to attention, and seems to be affected by task difficulty, which can affect the latency of the component (Polich, 2007).

A similar early attention related negative component, the selection negativity (SN) appearing ca 200 ms post stimulus, has also been found in the visual modality. According to Hillyard and Anllo-Vento, (1998) SN indexes feature discrimination and selection of a visual target stimuli. When trying to dissociate attention related to target feature selection from awareness, Koivisto and Revonsuo, (2008) observed a VAN component independently of selective attention, indexed by SN. VAN was elicited 100-200 ms after stimulus onset to both target and distractor stimuli. A later enhanced negativity of VAN was elicited 200-300 ms after stimulus onset. The authors suggested that the enhance late VAN was the result of attentional modulation due to SN. The LP component, however, was dependent strongly on selective attention. Since the early part of VAN did not depend on selective attention the authors suggested that VAN is an index for NCC proper in the visual domain, while the LP that depended on attention reflected later reflective cognitive processes.

2 Motivation and research hypothesis

Previous research into auditory awareness has mainly focused on identifying NCCs. Recently, research on modality-specific and modality-general electrophysiological correlates of visual and auditory awareness has also taken place. To date, little is known about how attention affects the recently discovered ERP components of auditory awareness. Furthermore, given

that there exists contradictory evidence as to how the LP is affected by response requirements there is also a need for more research into how the latter affects correlates of awareness in the auditory modality. The main goal of the present study was to examine how attention and response requirements affect AAN and LP using a syllable detection and discrimination task. By expanding on earlier research on auditory awareness we hope that the present study will add to our understanding on how the known components of auditory awareness vary under different circumstances. There is also a need for establishing new reliable methods to assess consciousness in patients who are in a deteriorated conscious state. Behavioural measures are still widely used to infer consciousness. However, these behavioural measurements are not perfect and misclassification sometimes occurs. Better methods for inferring consciousness would therefore be welcomed in both clinical and research settings (Koch et al., 2016; Kondziella et al., 2020).

Based on previous electrophysiological studies using auditory stimuli presented at the threshold of awareness (Eklund & Wiens, 2019) we expect to find differences between aware and unaware trials corresponding to the early AAN component, with an enhanced negative amplitude at the central electrode sites. For the LP component we expect an enhanced positivity at parietal and frontal electrodes. If AAN is affected by attention, we expect to see early effects of attention both before and during the AAN time window in fronto-central electrodes. If attention is more related to later stimulus categorization and selection, we expect to see effects during the LP time window.

3 Methods

3.1 Participants

45 healthy right-handed participants (age: $M = 25.15$ years, $SD = 3.98$) were recruited from the Turku area. Before taking part, participants gave their informed consent in accordance with the Declaration of Helsinki and the study was accepted by the local ethics committee. All participants reported normal or corrected-to-normal vision and normal hearing. The exclusion criteria were failure to calibrate individual auditory thresholds within 20%-80% of detection rate and noisy EEG data. Three participants were excluded from the study and 11 had to be excluded from the EEG analysis due to the insufficient number of trials for some experimental conditions.

3.2 Apparatus and Stimuli presentation

Stimulus presentation was carried out using PsychoPy (version, 3.0.7) on a Windows 10–based computer with a BENQ (model, XL2420-B) LCD monitor and a screen refresh rate of 60 Hz. The stimuli were presented binaurally using (Neuroscan, 10ohm $\frac{1}{4}$ stereo), in-ear earphones. Responses were recorded with an Xbox gaming control (model, 1708).

3.3 Procedure

The study implemented a GO-NOGO design with three near-threshold sound stimuli (syllables) “du”, “vi”, “me”), where target and non-target stimuli were counterbalanced across trial blocks. The three above-mentioned syllables were chosen because, the participants were able to discriminate between them when they were presented at near-threshold, during our pilot experiment. In the GO condition participants were asked to press the button (“A”) on the joystick if they heard the target stimulus and in the NOGO condition the same button should have been pressed if they did not hear the target stimulus. After the response participants were asked to rate their awareness on a modified version of the perceptual awareness scale (Ramsøy & Overgaard, 2004) which had three levels corresponding to whether the subjects heard the stimulus clearly, weakly or not at all. Awareness was rated after all trials, including non-target as well as empty catch trials. Go and NOGO conditions were counterbalanced: half of the participants had GO and the other half NOGO conditions in the first half of the experiment.

The experiment consisted of 6 blocks with 100 trials in each. Each block consisted of 25 target stimuli (one syllable), 50 non-target stimuli (other two syllables) and 25 catch empty trials. Each trial consisted of a blank grey screen presented for 900 ms followed by a pre-stimulus fixation cross, which was presented for 500 ms, a blank screen presented randomly for 500 - 1000 ms, followed by a stimulus phase, where a sound or catch trial was presented for 58 ms, a second fixation cross (in the form of letter “x”) presented for 300 ms, followed by a 20 ms blank screen. The trial ended with a perceptual awareness rating. A second fixation cross seemed helpful for participants to localise the time window of the sound according to our short pilot study and seemed to improve the task performance: otherwise, participants would have had to guess where the stimulus presentation ended and response phase began. The trial structure is shown in Figure 1.

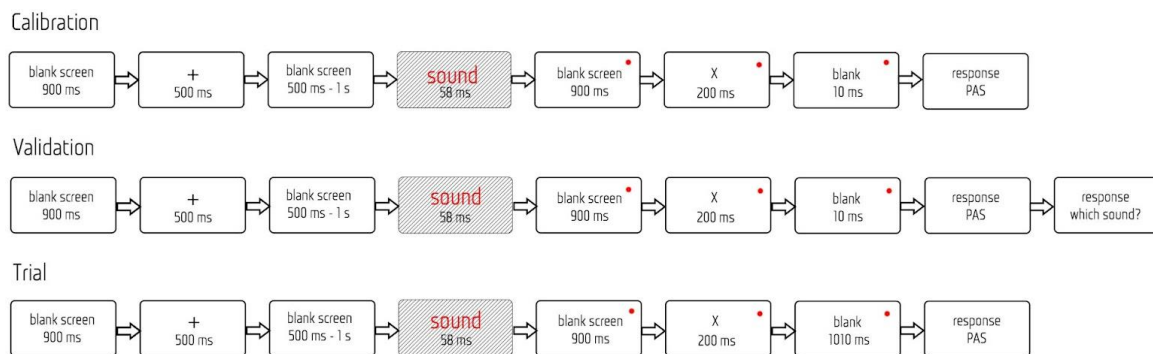


Figure 1: Trial structure

Red dot indicates the moment from when participants could press a button on a joystick.

Before the actual experiment, participants performed a practice task with 10 recognisable stimuli to better understand the procedure. The practice task implemented a GO condition. Participants also performed a calibration procedure consisting of one or two blocks having 160 and 120 trials respectively. Each of the three sounds were calibrated individually with the two-down-one-up staircase procedure. If any of the three thresholds could not be calculated after the first block, the calibration continued with the second block. After the calibration, participants performed a validation task, including awareness ratings and stimulus discrimination tasks. The inclusion criteria were 20-80% of awareness for each sound.

3.4 Electrophysiological recording

EEG signals were recorded using active 64 Ag/AgCl sintered ring electrodes attached to a recording cap (EASYCAP GmbH, Germany) and NeurOne system (Mega Electronics ltd) amplifier using a band pass of 0.05–100 Hz, with 500 Hz sampling rate. EEG was processed using EEGLAB (Delorme and Makeig, 2004) (version, 2021.1) and Matlab (version, R2021b).

3.5 Data analysis

Behavioural data were analysed with R (R Core Team, 2016) software. Analysis of variance (ANOVA) on awareness ratings was performed with Attention (2: target, non-target) x Condition (2: GO, NOGO) as factors. A separate ANOVA was performed on correct button presses in addition to the awareness ratings. Both “weakly” and “clearly” heard trials were counted as aware trials, since participants rarely report hearing the near-threshold stimuli clearly (Eklund & Wiens, 2019; Koivisto & Grassini, 2016).

The EEG was referenced to linked mastoids (average of electrodes TP9 and TP10). Baseline was corrected to activity 200 - 0 ms preceding the onset of the auditory stimulus. The EEGLAB function “pop_rejchan” was used to remove bad channels, with the options kurtosis, probability and spectrum checked using an absolute threshold of = 4sd. Additional visual inspection was performed before applying a 1 Hz high-pass filter (FIR, Hamming windowed; transition bandwidth, 1 Hz; filter order, 1650). The EEGLAB function “pop_cleanline” was performed to filter out line noise above 50 Hz. Interpolation was performed on the removed electrodes using the built-in spherical interpolation function in EEGLAB “pop_interp”. Low-pass filtering at 40 Hz was performed using the “eeg_filtnew” function in EEGLAB. Independent component analysis was performed, and artefactual ICA components were removed by manual inspection, visualised by ICLabel plugin (Pion-Tonachini, Kreutz-Delgado, Makeig, 2019) (version 1.3.). Remaining bad trials were rejected via EEGLAB function using joint probability on the recorded electrodes (local activity probability limit: 4sd, global limit: 2sd).

ERPs were analysed using Mass Univariate ERP Toolbox, MUT, (Groppe et al., 2011) which performs mass univariate analyses of event-related brain potentials and Factorial Mass Univariate ERP Toolbox, FMUT, (Fields & Kuperberg, 2020) which extends the MUT and implements ANOVA with Response (2: button press, no button press) Attention (2: target, non-target) & Awareness (2: aware, unaware) as factors. A factorial approach was chosen because of many experimental conditions, which, in turn, could make the results uninterpretable for methods like mixed effects models, which require a reference category. We analysed ERPs of all channels and time points in a 0 to 800 ms window. Due to the rare probability of some experimental conditions, such as pressing a button and reporting no awareness of the stimulus, these conditions had fewer trials than others. To test for statistical significance, we selected a non-parametric permutation approach with 1000 repetitions (Maris & Oostenveld, 2007) and performed permutation-based cluster mass correction (Groppe et al., 2011) to take into account clustering of effects. We choose the family-wise alpha of the test to be 0.05.

4 Results

4.1 Behaviour

Percentage of aware targets and non-targets in GO and NOGO conditions are shown in Figure 2. Attention x Condition ANOVA on awareness ratings was calculated for $N = 45$ to assess the influence of different factors on the proportion of overall awareness. The analysis shows a significant effect of attention on awareness $F(1, 44) = 6.12, p = 0.0173, \eta^2 0.24, 95\% \text{ CI } [0.01, 1.00]$. When taking into account correct responses the analysis shows significant effects of response $F(1, 44) = 35.28, p < 0.001, \eta^2 0.44, 95\% \text{ CI } [0.26, 1.00]$, attention $F(1, 44) = 6.12, p = 0.0173, \eta^2 0.24, 95\% \text{ CI } [0.01, 1.00]$, attention x response interaction $F(1, 44) = 8.64, p = 0.005, \eta^2 0.16, 95\% \text{ CI } [0.03, 1.00]$ as well as for attention x response x condition interaction ($F(1, 44) = 88.97, p < 0.001, \eta^2 0.67, 95\% \text{ CI } [0.53, 1.00]$).

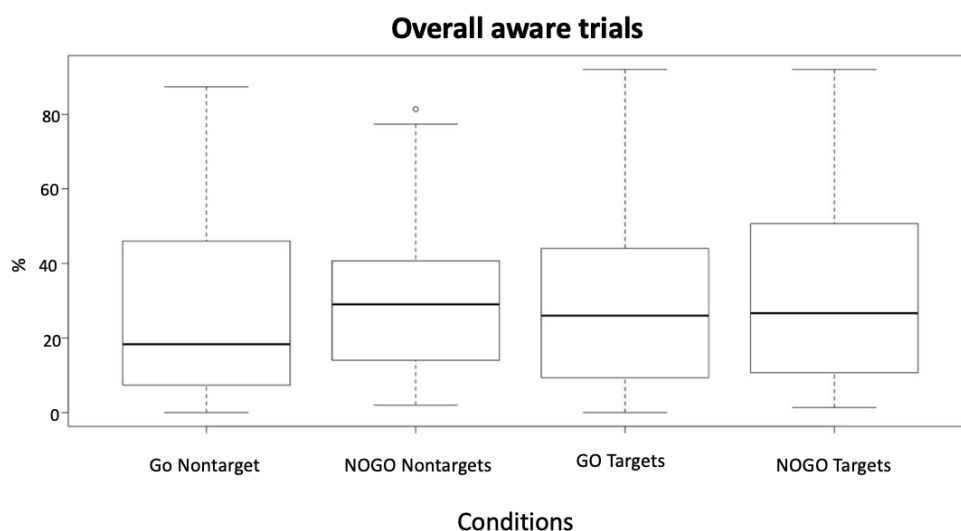


Figure 2. Shows percentage of overall aware trials for GO/NOGO targets and nontargets.

4.2 EEG

Event-related potentials (ERPs) were calculated for 34 participants. Grand averages of Fz and CPz electrodes sites are represented in Figure 3. Scalp topographies for the different conditions show aware-unaware differences in Figure 4. Results of mass univariate factorial analyses with response, attention and awareness as factors are represented in Figure 5.

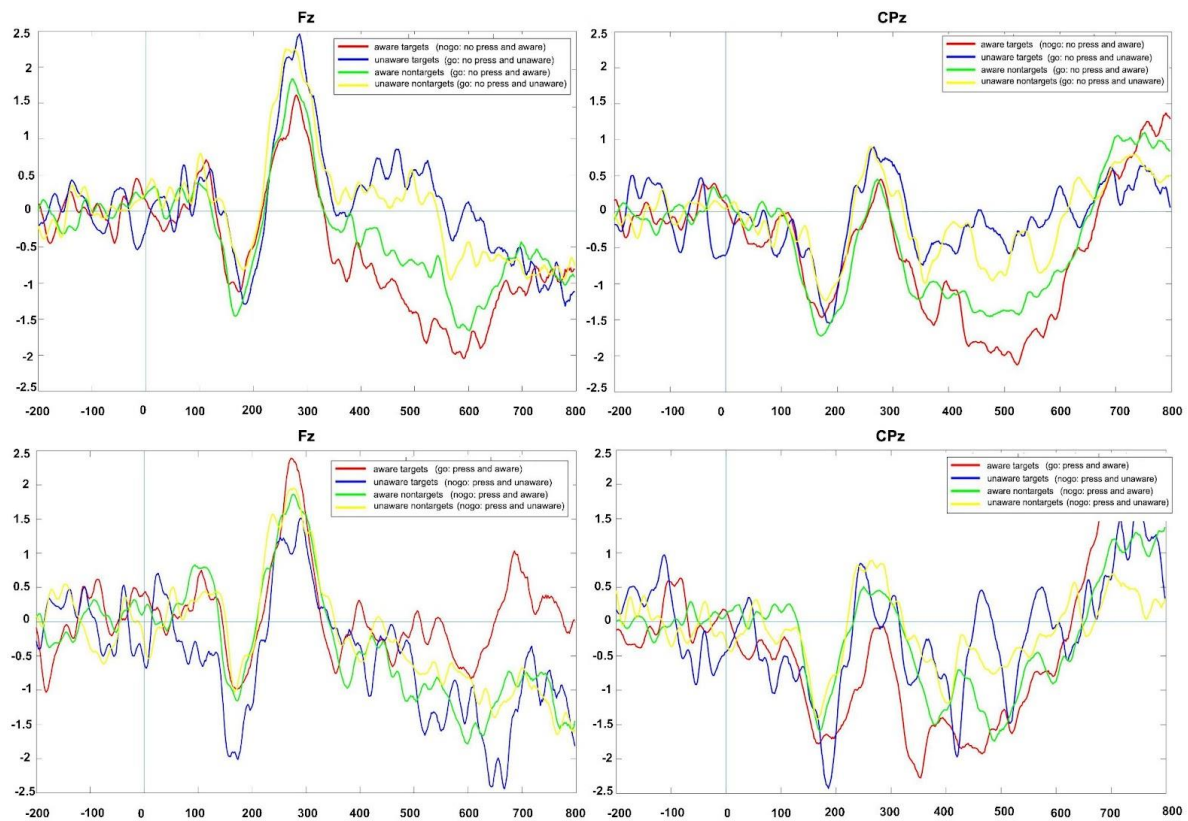


Figure 3. Grand averages for the different conditions. The upper panel shows electrodes CPz, Fz for aware trials without response. The colour coded lines denote different conditions: red represents aware targets without response (NOGO condition), blue represents unaware targets (GO condition), green represents aware non-targets (GO condition), yellow represents unaware non-targets (GO condition). The bottom panel shows the same electrodes but for aware trials with response: red represents aware targets (GO condition), blue represents unaware targets (NOGO condition), green represents aware non-targets (NOGO condition), yellow represents unaware non-targets (NOGO condition). Time on the x axis is in ms, and amplitude denoted on the y axis is in μV .

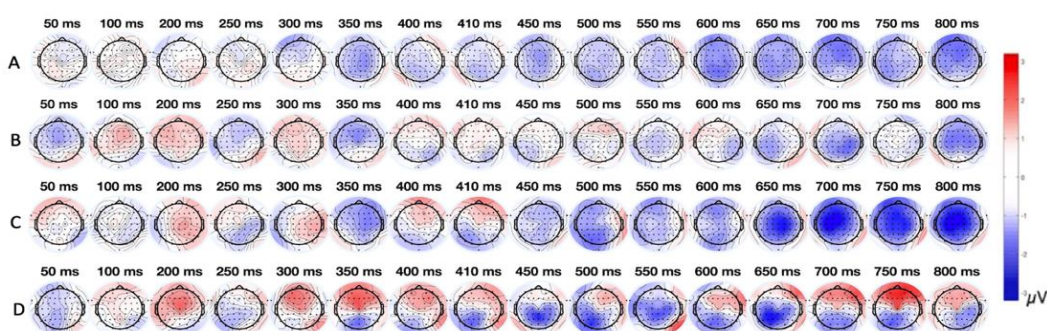


Figure 4. Shows scalp topographies of the different conditions. A) non targets without response, B) non targets with response, C) targets without response, D) targets with response.

The results of the scalp topographies of the different conditions in figure 4 show mainly negative activation in occipital, temporal and parietal regions in the AAN time window around 200 ms and onwards. Condition D that included targets as well as responses show

more positive activity in the mid-latency as well as late-latency LP time window starting from around 500 ms, similar to the grand averages of the same condition in figure 3.

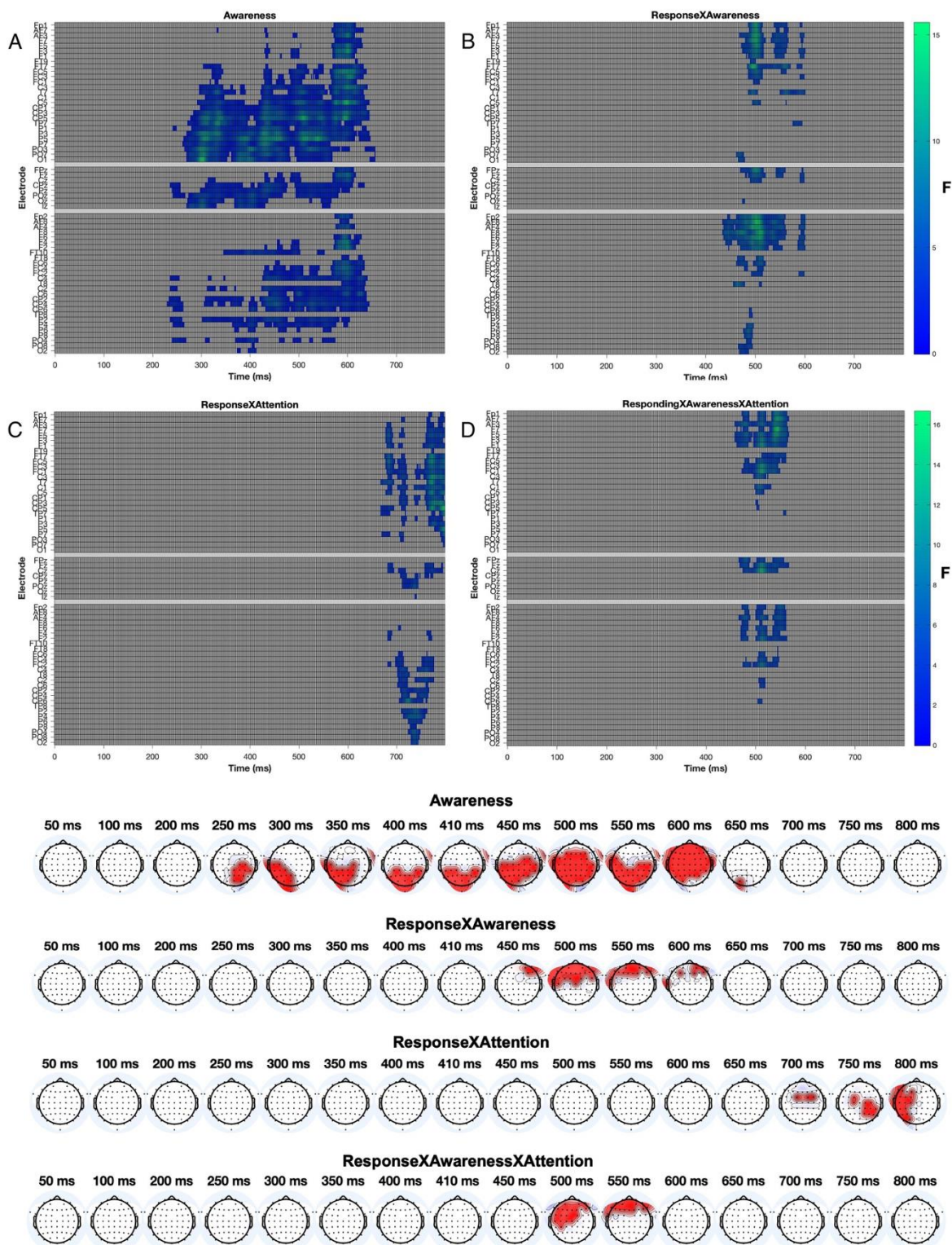


Figure 5. The upper panels show statistically significant contributions of each factor on the ERP amplitudes at each time point and electrode; colour denotes F value. The lower panels show the corresponding statistically significant effects on scalp topographic maps.

Figure 5 A shows the electrode locations where the signals were strengthened during aware trials. F values indicate significant clusters starting from around 250 ms in occipital-parietal areas, a cluster around 300 – 350 ms in parietal-temporal area, a cluster around 400-410 ms in posterior area, a cluster around 500 ms in posterior, temporal parietal as well as to some extent frontal areas, a cluster around 550 in occipital, temporal and parietal areas and a cluster around 600 ms in frontal, central and parietal areas. Comparing the statistically significant topographic maps in the lower panel of Figure 5, for awareness with the topographic maps for the different conditions in Figure 4, the significant activity corresponds mainly to negative activation in the same area, ranging from 250 ms to 550 ms. Hence there seems to be mainly significant negative activation, not related to LP, during the mid-latency LP or P3 time-window. Figure 5 B, shows activation related to awareness when response requirements are factored in. The activity is found mainly in frontal electrodes during mid-latency LP time window starting around 450 ms and lasting until 600 ms post stimulus.

In figure 5 D the F values in the mid-latency LP time-window starting from around 500 ms and extending to around 600 ms, shows mainly frontal activation with some additional central electrodes when attention and response requirements are factored in with awareness. In figure 5 C, significant F values in late LP time-window starting from around 700 ms stimulus onset indicate that the late LP was strengthened in connection to the task and attention interaction without awareness. These included a cluster of activation around 700 ms in the frontal area, and a cluster in frontal, temporal and parietal area at around 750 ms.

As figures indicate, AAN emerges in the posterior and left temporal region around 250 ms after stimulus onset and spreads to the central and parietal electrodes at least up to 400-450 ms post stimulus. The LP starts around 450 ms after stimulus onset and spreads up to 800 ms post stimulus. While the LP in general is present when attention and task relevance are factored in with awareness, the very late LP at around 700 ms post stimulus is present only for unaware trials. The prolonged negative activation after AAN might be an N400 ERP component which is related to semantic processing of the stimuli: additionally, the scalp distribution of AAN in its middle phases shows some left lateralisation, which indirectly supports this claim.

5 Discussion

The aim of the present study was to examine whether attention and response requirements affect AAN and LP ERP correlates of awareness. Unlike research in the visual modality, previous research in the auditory modality has mainly focused on awareness without assessing response requirements (Eklund & Wiens, 2019; Filimonov et al., 2022). A recent study by Eklund et al., (2019) reported that both AAN and early LP were present for both response and non-response trials, which contrasted with previous results from studies in the visual modality, where early LP was found to be affected by response requirements and attention (Koivisto et al., 2016). On the other hand, (Schlossmacher et al., 2021) reported that the LP was present only during task relevant stimuli requiring response. We implemented a GO-NOGO design in order to control for attention and response requirements separately. The results show a prolonged AAN for aware trials, a relatively late LP in 450 - 630 ms post stimulus when the interaction of response requirements was factored in with awareness, and a late LP starting from 500 ms post stimulus when both attention as well as response requirements were factored in with awareness and lastly from 700 ms post stimulus related to response requirements and attention but not awareness. The scalp topography of AAN was left lateralised possibly because the sound stimuli were syllables. We also found a negativity after around 400 ms after stimulus onset, which could be the language-related N400 component (Kutas & Federmeier, 2011).

The scalp topography of AAN showed left lateralisation, which contrasts with previous studies using bilateral stimuli (Eklund et al., 2019; Filimonov et al., 2022). A recent study looking at lateralisation of correlates of auditory awareness, found that the early AAN was lateralised for lateralised stimuli whereas LP did not show signs of lateralisation (Eklund et al., 2021). However, since we did not implement lateralised stimuli, it is doubtful that our lateralised AAN reflects the same phenomenon reported by (Eklund et al., 2021). Rather as mentioned above, a possible explanation for the left lateralisation is that the syllables were processed as speech. Earlier studies have found evidence for pre-attentive language processing in the left hemisphere (Alho et al., 1998; Näätänen et al., 1997). A tentative conclusion with regards to our results is that this pre-attentive language processing found in the left hemisphere starts as soon as awareness enters the scene during auditory processing, meaning that auditory awareness of speech also could be left-lateralised to some extent. However, since we did not include source reconstruction it is difficult to say with certainty

whether the present left-lateralised activity that showed up in temporal electrodes actually took place in the auditory cortex. The results are, however, consistent with the finding that previous studies have located the source of AAN to the bilateral auditory cortex, (Eklund et al., 2019). While we mainly found activity in the left hemisphere and not bilateral auditory cortex, Eklund et al., (2019) used simple tones as opposed to syllables, which could have led to bilateral activation instead of left-lateralization.

Additionally, the results show negative clusters starting at occipital areas around 250, followed by a cluster around 300-350 ms in the parietal-temporal area. The results differ from previous studies reporting fronto-central activation for AAN (Eklund et al., 2019; Schlossmacher et al., 2021), however, these studies used predefined electrodes as well as time windows to measure AAN. While it is common practice to use predefined time windows and electrodes to increase power when using conventional ERP analysis methods (Luck, 2014) this, however, leaves many areas un-searched, which can be detected using mass univariate analysis (Groppe et al., 2011). It is also worth noting that the above-mentioned studies used a different electrode montage and reference, which have been found to affect the results as well (Luck, 2014).

The latency of AAN was also prolonged, with negative activity being significant in temporo-parietal electrodes from around 300ms up to around 350 ms. A similar pattern for AAN being sustained into the mid-latency LP time window has also been reported in studies using more complex auditory stimuli, (Schlossmacher et al., 2021) or longer sound beeps (Gutschalk et al., 2008). While the syllables used in the present study were relatively short in duration (58 ms), they were more complex than sound beeps and this could have prolonged the processing time leading to a longer negativity or AAN.

The AAN was followed by a negative cluster around 400 ms starting in the posterior area that subsequently shifted to a more posterior, temporal and parietal area around 550 ms and a cluster around 600 ms in frontal, central and parietal areas. Auditory voice and semantic discrimination studies have found similar negative peaks appearing around 450 ms but appearing at left fronto-central regions (Shahin et al., 2006). Another interpretation, given the more posterior and temporal distribution found in the negative 400-450 ms time window, would be that the negative activity is the language-related N400 component, typically observed between 250 and 550 ms. The N400 has been found to occur in relation to a wide array of different stimuli, as long as the stimuli are meaningful, e.g., visual and auditory

words (and word-like strings of letters), acronyms. (Kutas & Federmeier, 2011). MEG and event-related optical signal (EROS) have also located the source of the N400 to the superior/middle temporal gyrus, the temporoparietal junction, the medial temporal lobe, and some frontal regions (Halgren et al., 2002; Helenius et al., 1998; Tse et al., 2007).

The results show a mid-latency LP at frontal and central electrode sites around 500-600 ms when the interaction of response requirements and attention was factored in with awareness as well as a mid-latency LP for response requirements and awareness interaction around 500 ms post stimulus. As for the late latency LP, the results show a fronto-parietal as well as to some extent temporal cluster at around 700-800 ms post stimulus related to response selection and attention but not awareness. A similar result was reached by (Schlossmacher et al., 2021) who reported AAN at 200 ms but no mid latency or late latency LP for task irrelevant conditions, however, when task relevance was factored in, both mid and late latency LP were enhanced suggesting that LP is not a correlate of awareness proper and mainly indexes some form of post-perceptual processing (Lamme, 2000).

The results are in line with the suggestion that LP indexes access consciousness, where competing stimuli are inhibited and task related stimuli are enhanced, or attended to, for further global processing (Koivisto & Grassini, 2016). The LP did however, occur at a later latency than has been reported in earlier studies (Eklund et al., 2019; Filimonov et al., 2022; Schlossmacher et al., 2021). A possible explanation for the delayed latency could be the complexity of the task (using three syllables instead of tone beeps, as well as changing the response requirements) (Kutas et al., 1977; Leckey & Federmeier, 2020). The task required participants to both detect and discern between stimuli, as well as to some extent inhibit their responses in the NOGO condition. These are all factors that have been found to be moderated by the frontal as well as to some extent parietal cortex (Aron et al., 2014; Osada et al., 2019). Furthermore, previous studies have shown that LP is sensitive to stimulus identification and semantics as well as response selection (Derda et al., 2019; Jimenez et al., 2018; Koivisto et al., 2016).

Previous studies, (Filimonov et al., 2022) have suggested that the LP be separated into an early modality-specific component possibly reflecting conscious access (Dehaene & Changeux, 2011) and a later modality-general, reflecting higher-level cognition. Our results seem to corroborate this claim, given that we found an early LP in relation to awareness, attention and response selection, while the later LP was associated with attention and response

selection. The results also fit with what some authors refer to as the level of processing hypothesis (Derda et al., 2019; Jimenez et al., 2018) where early correlates of awareness AAN / VAN are associated with awareness of lower-level stimulus properties whereas LP is associated with awareness of higher-level properties such as categories.

With regards to attention, our results point to no effect of attention during the AAN time window. Attended stimuli typically elicit more negative activity in fronto-central electrodes at around 100 ms. There are, however, many things that could have influenced attention in the way the experiment was conducted. If attention works as a gain control, (Hillyard et al., 1973) at an early stage of processing, presenting auditory stimuli that varies greatly in pitch and location makes it likely that attentional effects begin already in the cochlea. If the stimuli, however, are similar in both pitch and location, it is less likely to see early attentional effects since both attended and ignored stimuli are coded by the same pools of neurons until a later stage of processing (Luck & Kappenman, 2011).

It is possible that the syllables used in the present study failed to elicit more negative activity in fronto-central electrodes during the early stage of processing since they were too similar in pitch and appeared bilaterally. Earlier ERP studies have also found that early attentional effects are diminished when differences between attended and unattended stimuli are reduced, (Hansen & Hillyard, 1983). The results are also in line with research pointing to attentional modulation at both early and late stages of perceptual processing depending on e.g., stimulus and task parameters (Vogel et al., 2005).

When interviewing the subjects after the experiments, some mentioned that for example differentiating between VI and ME was difficult, even if the syllables seemed to work during the pilot experiment. This could have postponed the attentional effect to a later stage where a more top-down evaluation was made as to the nature of the stimulus. In accordance with this we did manage to find significant effects of attention and response requirement interactions both with and without awareness at a later stage, and this could be taken to index later attentional processing plus other task related cognitive operations (Derda et al., 2019; Jimenez et al., 2018; Koivisto et al., 2017).

With regards to stimulus presentation rate, previous studies have shown that a rapid presentation rate (typically, two to four stimuli per second) is to be favoured if the goal is to test attentional effects on early sensory processing (Lavie, 1995). Conversely, if the stimulus is presented with a slow rate, there is ample time for the brain to process the stimulus and no

need for early attentional modulation (Hansen & Hillyard, 1980; Woldorff & Hillyard, 1991). In the present study only one syllable was presented at the time, which could have abolished the need for early attentional modulation of sensory input at an early stage of processing.

Lastly, it is worth noting that the present study differed from previous studies in many ways. First and foremost, we did not include preselected electrodes or time-windows for measuring AAN and LP as has been the case in most previous studies (Eklund et al., 2019; Eklund & Wiens, 2019). We chose to perform factorial mass univariate analysis in order to get a more nuanced picture of how the electrophysiological correlates of awareness are affected by both response requirements and attention. The method, like all methods, has both its pros and cons. Firstly, by not having preselected time-windows we were able to measure effects related to AAN and LP outside the conventional time-windows and electrodes, and our results show that AAN can be prolonged, possibly due to stimulus complexity. Instead of mid-latency LP at 350-550 ms we observed negative activation probably similar to the semantically related N400. As for the late LP, the results show a clear effect of response requirements at around 450 ms, attention as well as response requirements at around 500 ms but also at around 700 ms post stimulus for the same factors without awareness. The downside of using mass univariate analysis, is that so called unexpected effects can be found when having such a broad analysis window while at the same time analysing all electrodes. Simulation studies have also found that, compared to conventional approaches, mass univariate analysis can yield more false negatives as the control for multiple comparisons is more rigorous. However, a decrease in power is not usually found for large components like the P3 that make up the LP (Groppe et al., 2011).

5.1 Further developments

Our results seem to support the view that early electrophysiological correlates belonging to the PAN-family are the true correlates of phenomenal consciousness. AAN is the true auditory NCC and different parts of the LP seem to be related to reflective consciousness and other cognitive processes, such as attention and response selection.

We see several implications for future research on the neural correlates of consciousness. First, future studies need to investigate further the possible dissociation between AAN and the attention related PN, utilising different experimental designs and stimulus. In the present study we did not find an effect of attention in AAN/PN time window, however, as discussed, there are factors related to the current study which might have influenced the results.

Therefore, additional research on dissociating attention and consciousness in the early N1-N2 time window is required.

Another line of further research could be related to our result regarding lateralisation of auditory NCCs for specific sounds (contents of consciousness). Future studies could implement both syllables that confer semantic meaning as well as other non-meaningful sounds of similar complexity and length. This could help to clarify whether the negative activity seen from 400 ms post stimulus is actually related to semantic processing of the syllables, but also to clear up whether AAN is left-lateralised for speech-like stimuli. However, such studies would require EEG source reconstruction and special stimuli which could be perceived as either having semantic dimension or not. This, in turn, could shed light on which stimulus features are processed unilaterally or bilaterally and which NCCs are involved in this content-specific lateralisation.

Finally, given our results we think that further research on LP is warranted. First, to test AAN and LP against the level of processing hypothesis (LoP), which postulates a two-stage model of conscious perception, where basic stimulus features are processed by early NCCs in the PAN-family, while LP is related to higher level features. Since our results seem to point to LP having two parts, it would be an important further step to investigate what part of LP corresponds to higher level feature processing, if indeed such a distinction can be made.

5.2 Conclusion

When controlling for attention and response requirements using a GO-NOGO task, the results show a prolonged left-lateralised AAN for aware trials. AAN was not associated with attention and response requirements suggesting that it might be the earliest correlate of awareness in the auditory modality. We also found a negativity after around 400 ms after stimulus onset, which could be the language-related N400, due to the use of syllables as stimuli. A mid-latency LP in 450 - 600 ms post stimulus was found when the interaction of response requirements was factored in with awareness, a mid-latency LP effect for both attention and response requirement and awareness interaction at around 500 ms and a late LP starting from 700 ms post stimulus related to response selection and attention but not awareness. Given the two-part structure of the LP component, the result seems to corroborate earlier studies suggesting the earlier part of LP is domain-specific, while the later part is domain-general. The effects of both attention as well as response requirements on LP seem to

point to the latter being a correlate of later cognitive processes in addition to awareness and not a correlate of awareness per se.

References

- Alho, K., Connolly, J. F., Cheour, M., Lehtokoski, A., Huotilainen, M., Virtanen, J., Aulanko, R., & Ilmoniemi, R. J. (1998). Hemispheric lateralization in preattentive processing of speech sounds. *Neuroscience Letters*, *258*(1), 9–12. [https://doi.org/10.1016/S0304-3940\(98\)00836-2](https://doi.org/10.1016/S0304-3940(98)00836-2)
- Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: One decade on. *Trends in Cognitive Sciences*, *18*(4), 177–185. <https://doi.org/10.1016/j.tics.2013.12.003>
- Aru, J., Bachmann, T., Singer, W., & Melloni, L. (2012). Distilling the neural correlates of consciousness. *Neuroscience & Biobehavioral Reviews*, *36*(2), 737–746. <https://doi.org/10.1016/j.neubiorev.2011.12.003>
- Auksztulewicz, R., Spitzer, B., & Blankenburg, F. (2012). Recurrent Neural Processing and Somatosensory Awareness. *Journal of Neuroscience*, *32*(3), 799–805. <https://doi.org/10.1523/JNEUROSCI.3974-11.2012>
- Block, N. (1995). On a confusion about a function of consciousness. *Behavioral and Brain Sciences*, *18*(2), 227–247. <https://doi.org/10.1017/S0140525X00038188>
- Chalmers, D. J. (2000). What is a Neural Correlate of Consciousness? In T. Metzinger (Ed.), *Neural Correlates of Consciousness* (pp. 17–39). MIT Press.
- Crick, F., & Koch, C. (1990). Towards a neurobiological. *Seminars in the Neurosciences*, *2*, 263–275.
- Crick, F., & Koch, C. (1998). Consciousness and neuroscience. *Cerebral Cortex*, *8*(2), 97–107. <https://doi.org/10.1093/cercor/8.2.97>
- Dehaene, S., & Changeux, J.-P. (2011). Experimental and Theoretical Approaches to Conscious Processing. *Neuron*, *70*(2), 200–227. <https://doi.org/10.1016/j.neuron.2011.03.018>
- Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition*, *79*(1–2), 1–37. [https://doi.org/10.1016/S0010-0277\(00\)00123-2](https://doi.org/10.1016/S0010-0277(00)00123-2)

- Dembski, C., Koch, C., & Pitts, M. (2021). Perceptual awareness negativity: A physiological correlate of sensory consciousness. *Trends in Cognitive Sciences*, 25(8), 660–670.
<https://doi.org/10.1016/j.tics.2021.05.009>
- Derda, M., Koculak, M., Windey, B., Gociewicz, K., Wierzchoń, M., Cleeremans, A., & Binder, M. (2019). The role of levels of processing in disentangling the ERP signatures of conscious visual processing. *Consciousness and Cognition*, 73, 102767.
<https://doi.org/10.1016/j.concog.2019.102767>
- Deutsch, J. A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review*, 70(1), 80–90. <https://doi.org/10.1037/h0039515>
- Eklund, R., Gerdfeldter, B., & Wiens, S. (2019). Effects of a Manual Response Requirement on Early and Late Correlates of Auditory Awareness. *Frontiers in Psychology*, 10, 2083.
<https://doi.org/10.3389/fpsyg.2019.02083>
- Eklund, R., Gerdfeldter, B., & Wiens, S. (2021). The early but not the late neural correlate of auditory awareness reflects lateralized experiences. *Neuropsychologia*, 158, 107910.
<https://doi.org/10.1016/j.neuropsychologia.2021.107910>
- Eklund, R., & Wiens, S. (2019). Auditory awareness negativity is an electrophysiological correlate of awareness in an auditory threshold task. *Consciousness and Cognition*, 71, 70–78.
<https://doi.org/10.1016/j.concog.2019.03.008>
- Fields, E. C., & Kuperberg, G. R. (2020). Having your cake and eating it too: Flexibility and power with mass univariate statistics for ERP data. *Psychophysiology*, 57(2), e13468.
<https://doi.org/10.1111/psyp.13468>
- Filimonov, D., Railo, H., Revonsuo, A., & Koivisto, M. (2022). Modality-specific and modality-general electrophysiological correlates of visual and auditory awareness: Evidence from a bimodal ERP experiment. *Neuropsychologia*, 166, 108154.
<https://doi.org/10.1016/j.neuropsychologia.2022.108154>
- Förster, J., Koivisto, M., & Revonsuo, A. (2020). ERP and MEG correlates of visual consciousness: The second decade. *Consciousness and Cognition*, 80, 102917.
<https://doi.org/10.1016/j.concog.2020.102917>

- Giard, M.-H. (2000). Neurophysiological mechanisms of auditory selective attention in humans. *Frontiers in Bioscience*, 5(1), d84. <https://doi.org/10.2741/Giard>
- Groppe, D. M., Urbach, T. P., & Kutas, M. (2011). Mass univariate analysis of event-related brain potentials/fields I: A critical tutorial review: Mass univariate analysis of ERPs/ERFs I: Review. *Psychophysiology*, 48(12), 1711–1725. <https://doi.org/10.1111/j.1469-8986.2011.01273.x>
- Gutschalk, A., Micheyl, C., & Oxenham, A. J. (2008). Neural Correlates of Auditory Perceptual Awareness under Informational Masking. *PLoS Biology*, 6(6), e138. <https://doi.org/10.1371/journal.pbio.0060138>
- Halgren, E., Dhond, R. P., Christensen, N., Van Petten, C., Marinkovic, K., Lewine, J. D., & Dale, A. M. (2002). N400-like Magnetoencephalography Responses Modulated by Semantic Context, Word Frequency, and Lexical Class in Sentences. *NeuroImage*, 17(3), 1101–1116. <https://doi.org/10.1006/nimg.2002.1268>
- Hansen, J. C., & Hillyard, S. A. (1980). Endogenous brain potentials associated with selective auditory attention. *Electroencephalography and Clinical Neurophysiology*, 49(3–4), 277–290. [https://doi.org/10.1016/0013-4694\(80\)90222-9](https://doi.org/10.1016/0013-4694(80)90222-9)
- Hansen, J. C., & Hillyard, S. A. (1983). Selective attention to multidimensional auditory stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, 9(1), 1–19. <https://doi.org/10.1037/0096-1523.9.1.1>
- Helenius, P., Salmelin, R., Service, E., & Connolly, J. F. (1998). Distinct time courses of word and context comprehension in the left temporal cortex. *Brain*, 121(6), 1133–1142. <https://doi.org/10.1093/brain/121.6.1133>
- Hillyard, S. A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. *Proceedings of the National Academy of Sciences*, 95(3), 781–787. <https://doi.org/10.1073/pnas.95.3.781>
- Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical Signs of Selective Attention in the Human Brain. *Science*, 182(4108), 177–180. <https://doi.org/10.1126/science.182.4108.177>

- Jimenez, M., Grassini, S., Montoro, P. R., Luna, D., & Koivisto, M. (2018). Neural correlates of visual awareness at stimulus low vs. High-levels of processing. *Neuropsychologia*, *121*, 144–152.
<https://doi.org/10.1016/j.neuropsychologia.2018.11.001>
- Koch, C. (2004). *The quest for consciousness: A neurobiological approach*. Roberts and Co.
- Koch, C., Massimini, M., Boly, M., & Tononi, G. (2016). Neural correlates of consciousness: Progress and problems. *Nature Reviews Neuroscience*, *17*(5), 307–321.
<https://doi.org/10.1038/nrn.2016.22>
- Koivisto, M., & Grassini, S. (2016). Neural processing around 200 ms after stimulus-onset correlates with subjective visual awareness. *Neuropsychologia*, *84*, 235–243.
<https://doi.org/10.1016/j.neuropsychologia.2016.02.024>
- Koivisto, M., Grassini, S., Salminen-Vaparanta, N., & Revonsuo, A. (2017). Different Electrophysiological Correlates of Visual Awareness for Detection and Identification. *Journal of Cognitive Neuroscience*, *29*(9), 1621–1631. https://doi.org/10.1162/jocn_a_01149
- Koivisto, M., & Revonsuo, A. (2008). The role of selective attention in visual awareness of stimulus features: Electrophysiological studies. *Cognitive, Affective, & Behavioral Neuroscience*, *8*(2), 195–210. <https://doi.org/10.3758/CABN.8.2.195>
- Koivisto, M., & Revonsuo, A. (2010). Event-related brain potential correlates of visual awareness. *Neuroscience & Biobehavioral Reviews*, *34*(6), 922–934.
<https://doi.org/10.1016/j.neubiorev.2009.12.002>
- Koivisto, M., Salminen-Vaparanta, N., Grassini, S., & Revonsuo, A. (2016). Subjective visual awareness emerges prior to P3. *European Journal of Neuroscience*, *43*(12), 1601–1611.
<https://doi.org/10.1111/ejn.13264>
- Kondziella, D., Bender, A., Diserens, K., van Erp, W., Estraneo, A., Formisano, R., Laureys, S., Naccache, L., Ozturk, S., Rohaut, B., Sitt, J. D., Stender, J., Tiainen, M., Rossetti, A. O., Gosseries, O., Chatelle, C., & the EAN Panel on Coma, Disorders of Consciousness. (2020). European Academy of Neurology guideline on the diagnosis of coma and other disorders of consciousness. *European Journal of Neurology*, *27*(5), 741–756.
<https://doi.org/10.1111/ene.14151>

- Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event related brain potential (ERP). *Annual Review of Psychology*, *62*, 621–647. <https://doi.org/10.1146/annurev.psych.093008.131123>
- Kutas, M., McCarthy, G., & Donchin, E. (1977). Augmenting Mental Chronometry: The P300 as a Measure of Stimulus Evaluation Time. *Science*, *197*(4305), 792–795. <https://doi.org/10.1126/science.887923>
- Lamme, V. A. F. (2000). Neural Mechanisms of Visual Awareness: A Linking Proposition. *Brain and Mind*, *1*(3), 385–406. <https://doi.org/10.1023/A:1011569019782>
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(3), 451–468. <https://doi.org/10.1037/0096-1523.21.3.451>
- Leckey, M., & Federmeier, K. D. (2020). The P3b and P600(s): Positive contributions to language comprehension. *Psychophysiology*, *57*(7), e13351. <https://doi.org/10.1111/psyp.13351>
- Luck, S. J. (2014). *An introduction to the event-related potential technique* (Second edition). The MIT Press.
- Luck, S. J., & Kappenman, E. S. (2011). *ERP Components and Selective Attention*. Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780195374148.013.0144>
- Marinato, G., & Baldauf, D. (2019). Object-based attention in complex, naturalistic auditory streams. *Scientific Reports*, *9*(1), 2854. <https://doi.org/10.1038/s41598-019-39166-6>
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. <https://doi.org/10.1016/j.jneumeth.2007.03.024>
- Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, *42*(4), 313–329. [https://doi.org/10.1016/0001-6918\(78\)90006-9](https://doi.org/10.1016/0001-6918(78)90006-9)
- Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., Vainio, M., Alku, P., Ilmoniemi, R. J., Luuk, A., Allik, J., Sinkkonen, J., & Alho, K. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature*, *385*(6615), 432–434. <https://doi.org/10.1038/385432a0>

- Osada, T., Ohta, S., Ogawa, A., Tanaka, M., Suda, A., Kamagata, K., Hori, M., Aoki, S., Shimo, Y., Hattori, N., Shimizu, T., Enomoto, H., Hanajima, R., Ugawa, Y., & Konishi, S. (2019). An Essential Role of the Intraparietal Sulcus in Response Inhibition Predicted by Parcellation-Based Network. *Journal of Neuroscience*, *39*(13), 2509–2521.
<https://doi.org/10.1523/JNEUROSCI.2244-18.2019>
- Polich, J. (2007). Updating P300: An Integrative Theory of P3a and P3b. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, *118*(10), 2128–2148. <https://doi.org/10.1016/j.clinph.2007.04.019>
- Ramsøy, T. Z., & Overgaard, M. (2004). Introspection and subliminal perception. *Phenomenology and the Cognitive Sciences*, *3*(1), 1–23. <https://doi.org/10.1023/B:PHEN.0000041900.30172.e8>
- Revonsuo, A. (2009). *Inner presence: Consciousness as a biological phenomenon*. MIT Press.
- Schlossmacher, I., Dellert, T., Bruchmann, M., & Straube, T. (2021). Dissociating neural correlates of consciousness and task relevance during auditory processing. *NeuroImage*, *228*, 117712.
<https://doi.org/10.1016/j.neuroimage.2020.117712>
- Shahin, A. J., Alain, C., & Picton, T. W. (2006). Scalp Topography and Intracerebral Sources for ERPs Recorded During Auditory Target Detection. *Brain Topography*, *19*(1), 89–105.
<https://doi.org/10.1007/s10548-006-0015-9>
- Treisman, A. M., & Riley, J. G. (1969). Is selective attention selective perception or selective response? A further test. *Journal of Experimental Psychology*, *79*(1, Pt.1), 27–34.
<https://doi.org/10.1037/h0026890>
- Tse, C.-Y., Lee, C.-L., Sullivan, J., Garnsey, S. M., Dell, G. S., Fabiani, M., & Gratton, G. (2007). Imaging cortical dynamics of language processing with the event-related optical signal. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(43), 17157–17162. <https://doi.org/10.1073/pnas.0707901104>
- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2005). Pushing around the Locus of Selection: Evidence for the Flexible-selection Hypothesis. *Journal of Cognitive Neuroscience*, *17*(12), 1907–1922.
<https://doi.org/10.1162/089892905775008599>

- Woldorff, M. G., Gallen, C. C., Hampson, S. A., Hillyard, S. A., Pantev, C., Sobel, D., & Bloom, F. E. (1993). Modulation of early sensory processing in human auditory cortex during auditory selective attention. *Proceedings of the National Academy of Sciences*, *90*(18), 8722–8726. <https://doi.org/10.1073/pnas.90.18.8722>
- Woldorff, M. G., & Hillyard, S. A. (1991). Modulation of early auditory processing during selective listening to rapidly presented tones. *Electroencephalography and Clinical Neurophysiology*, *79*(3), 170–191. [https://doi.org/10.1016/0013-4694\(91\)90136-R](https://doi.org/10.1016/0013-4694(91)90136-R)
- Ye, M., & Lyu, Y. (2019). Later Positivity Reflects Post-perceptual Processes: Evidence From Immediate Detection and Delayed Detection Tasks. *Frontiers in Psychology*, *10*. <https://www.frontiersin.org/article/10.3389/fpsyg.2019.00082>