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Comparing Auditory and Visual Electrophysiological Markers of Consciousness in Bimodal Stimuli

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Abstract

Neural correlates of consciousness indicate specific neural processes that are linked to conscious experiences. Auditory awareness negativity (AAN) and Visual awareness negativity (VAN) have been suggested as the candidates of early sensory processing while, Lateral positivity (LP) is believed to reflect the post perceptual processing like attention, decision making and response selection.

This study investigated the auditory and visual electrophysiological markers of consciousness in bimodal conditions using a GO/NOGO task. Participants were asked to report their perceptual awareness of near threshold auditory and visual stimuli while the EEG was recorded. Because of the ongoing nature of the larger project, the current study examines specifically unattended, non-target bimodal trials, allowing the examination of awareness related neural activity while reducing the response related confounds.

Results showed that both AAN and VAN are consistently differentiated aware from unaware stimuli across auditory and visual modalities, with differences in latency and their topographical distributions. On the other hand, LP effects were less consistent and varied across modalities suggesting its role in post perceptual processing rather than awareness. Overall, these findings suggest that AAN and VAN are related to early sensory processing, whereas LP reflects later cognitive processing.

Key words: Neural Correlate of Consciousness (NCC), awareness, attention, Auditory awareness negativity (AAN), Visual awareness negativity (VAN), Lateral Positivity (LP), GO/NOGO task, Sensory discrimination task.

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1 Introduction

The neural correlates of consciousness (NCC) are defined as the smallest sets of neuronal events that are enough to produce conscious experience (Crick & Koch, 1995). This definition can be interpreted in two ways, based on whether one addressing to the specific contents of consciousness or to conscious experience as a whole. Content-specific NCC refers to neurons, neural populations, or networks that are associated with a specific conscious experience. For example, when a person perceives a face, specific neurons in face-selective regions of visual cortex fire. If these neurons were artificially stimulated, the person might experience seeing a face even in the absence of external stimulus. Conversely, if their activity were blocked, face perception would be impaired even when a face is present. On the other hand, the full-content NCC refers to the neural processes that give rise to the overall conscious state, encompassing the combination of specific contents at a given moment. These mechanisms can be viewed as the integration of multiple-content NCC, such that modifying any of them would change the overall conscious experience. It is also important to distinguish NCC from background conditions that does not directly involved in consciousness but are necessary for brain functioning like glucose supply or oxygen levels (Koch et al., 2016).

Although these differentiations clarify different types of NCC, but it is important to note that NCC explain patterns of neural activity related to consciousness without indicating a direct causal relationship. A neural correlate of consciousness refers to a specific arrangement of brain activity that reliably accompanies a specific conscious experience. How physical mechanism, such as neuronal activity, give rise to subjective experiences such as awareness remains a central philosophical challenge. Consequently, the search of neural correlate of consciousness is mainly an empirical investigation, seeking to point out and describe patterns of neural activity that are specifically related with conscious experience, instead of unconscious perception or action (Rees et al., 2002)

Much of the empirical research on NCC has relied on contrastive analysis, in which neural activity is compared between consciously perceived and unperceived instances of the same stimulus. However, concerns have been raised regarding whether this method reliably isolates the neural mechanisms that directly constitute conscious experience. Differences observed between conscious and unconscious processing may reflect not only NCC proper, neural events that enables conscious processing, but also processes that occur before or after awareness. Neural events that that enable conscious perception without constituting it are referred to as "NCC-prerequisites" (NCCpr), whereas neural events that precedes conscious experience, such as reporting or decision making, are labelled as "NCC-consequences" or "NCC aftereffects" (NCCae). Therefore it is important to separate 'NCC-proper' from these related processes to isolate true neural basis of consciousness (Aru et al., 2012; De Graaf, Hsieh, & Sack, 2004; Paulewicz & Wierzchon, 2015).

1.1 Theories of consciousness

Besides the NCC themselves, to comprehend the nature of brain activity and conscious experience requires theoretical evaluation of the empirical findings. To date, theories of consciousness propose diverse and sometimes opposite explanations of the existing experimental evidence (Seth & Bayne, 2022). A central debate concerns whether conscious awareness associated with anterior (frontal) or posterior brain regions. Some theories emphasize the role of frontal cortex in consciousness and higher-order cognitive activities, whereas other emphasize the role of posterior sensory brain regions for conscious awareness. Among prominent theories that directly address NCC within the NCC framework is the Global Neuronal Workspace Theory (GNWT). According to GNWT, consciousness arises through a process of ignition, whereby stimulus-related information becomes globally available within a distributed neuronal workspace, primarily involving frontoparietal cortical regions (Dehaene, 2001; Seth & Bayne, 2022). Here, the term ignition defined as synchronized activation of neurons in brain that gain access to the global workspace, either in response to an external stimulus, or it may occur instinctively and randomly at rest. Once ignited, information is broadcast to multiple brain regions, including prefrontal cortex, anterior temporal cortex, inferior parietal cortex and anterior and posterior cingulate cortices for further cognitive processes such as memory, motor, evaluation and attention (Baars, 1995; Mashour et al., 2020).

Recurrent Processing Theory (RPT) proposes that consciousness emerges from feedback (recurrent) processing both within sensory cortices and between sensory and higher-level cortical regions. Based on this, conscious perception arises when lower-level sensory regions and higher-level cortical regions exchange information through recurrent loops. Unlike Global Neuronal Workspace Theory, which emphasizes the necessity of frontal regions, Recurrent Processing Theory proposed that posterior sensory regions are enough for conscious perception(Seth & Bayne, 2022). Recurrent Processing Theory suggested two stages of neural processing: an initial feedforward sweep in which sensory information is transferred from lower-level to higher-level cortical areas in a largely automatic, pre-attentive, and unconscious manner. This stage quickly processed basic features and general categories of stimulus without producing conscious perception. The second stage involves recurrent processing, characterized by feedback and lateral interactions between higher-level and lower-level cortical areas, allowing attention and integration of information, which leads to conscious perception (Allen et al., 2020; Kietzmann et al., 2019; Lamme & Roelfsema, 2000).

Apart from Global Neuronal Workspace Theory and Recurrent Processing Theory, there are other prominent theories that explain consciousness with different perspectives. Integrated Information Theory (IIT) posits that consciousness is equivalent to the system's capacity to integrate information, defined in terms of its intrinsic cause-effect structure. According to IIT, consciousness depends on how strongly system components constrain each other, forming a unified whole. This framework links consciousness to posterior cortical regions, unlike Global Neuronal Work Space Theory by emphasizing on intrinsic causal structure rather than information broadcasting or cognitive access (Seth & Bayne, 2022; Tononi, 2004, 2008).

Higher-Order Theories (HOT) propose that consciousness relies on the meta representations of lower-order perceptual states (Carruthers, 2000; Odegaard et al., 2017; Rosenthal, n.d.). In this view, sensory processing can happen unconsciously at lower levels, but a mental state becomes conscious only when it is represented by higher-order awareness. Recent evidence proposed that this higher-order evaluation may involve frontoparietal cortical networks that enable perceptual states become accessible for reporting and reflection (Odegaard et al., 2017). In short, Higher Order Theories suggest that consciousness does not emerge from perception alone but from the brain's awareness of its own perceptual states.

Predictive Processing Theory propose the idea that perception reflects Bayesian inference about the cause of sensory input (Clark, 2013). This framework is closely related to the Free Energy Principle, which proposes that biological systems, including the brain, act to reduce surprise and maintain stability overtime (Friston, 2010, Friston & Kiebel, 2009, Seth & Tsakiris, n.d.). This viewpoint leads to the idea that brain continuously produces predictions about sensory input and updates them by minimizing prediction errors through reciprocal exchange between higher and lower cortical areas (Rao & Ballard, 1999, Hohwy, Jakob, 2013). But this debate is still unresolved and it is believed that multiple interactions among different brain regions are required for conscious awareness rather than a single locus (Seth & Bayne, 2022).

While these theories provide theoretical frameworks for understanding consciousness, researchers have highlighted that differences in stimulus features, task demands, and processing levels may lead to difficulties in isolating the true NCC. Consequently, determining whether a given pattern of brain activity qualifies as NCC proper, rather than NCC prerequisites (NCCpr) or NCC consequences (NCCae) is challenging. Ideally, this would require manipulating NCCpr and NCCae while keeping the physical properties of stimulus constant. This is impossible to attain through contrastive analysis experimental approaches alone. Evidence shows that later ERP components show sensitivity to post-perceptual processes such as stimulus expectancy (Melloni et al., 2011), task relevance (Pitts et al., 2014), and attentional selection (Koivisto & Revonsuo, 2008). Therefore, many researchers proposed that later ERP components indicate processes that arise after conscious awareness, whereas earlier ERP components are more likely to occur at earlier stages of neural processing. Importantly, this interpretation applies particularly to ERP measures and does not imply that neural correlates of consciousness are limited to ERPs (Railo et al., 2011).

Another complication arises from variability in the stimulus feature evaluation, which is rarely controlled in studies of consciousness (Windey et al., 2013). Conscious awareness of low-level features (e.g., colour or shape) (Windey et al., 2013) and high-level features (e.g., semantic meaning or numeric magnitude) (Anzulewicz et al., 2015; Windey et al., 2013) may involve different neuronal activity patterns, resulting in different subjective visibility ratings. By manipulating the level of processing (LoP) through task instructions, previous studies have showed changes in subjective awareness reports without affecting objective performance, or without modulating the association between visibility and performance (Windey et al., 2014). In these experiments, the physical properties of the stimulus remains constant across conditions, allowing researchers to regulate for perceptual confounds that might otherwise affect conscious processing.

Among the various methods used to study NCC, electroencephalography (EEG) is a reliable instrument to explore the neural responses to stimuli at a millisecond time scale, particularly during cognitive tasks (Crick & Koch, n.d.; Förster et al., 2020; Koch et al., 2016). EEG measures electrical signals recorded at the scalp that predominantly reflect synchronized neural activity but are also influenced by muscle activity, eye movements, and environmental noise (Angelovska & Roehm, 2023). While EEG provides fine temporal details, its spatial resolution is limited, therefore it is often combined with complementary approaches such as functional magnetic resonance imaging (fMRI) or magnetoencephalography (MEG) to improve source localization (Koch et al., 2016; Melloni et al., 2007).

Event-related potentials (ERPs) are time-locked changes in the scalp-recorded electrical potential that are associated with sensory, cognitive, or motor events. ERPs provide important information about the temporal dynamic of conscious perception allowing researchers to differentiate between early and late conscious processing. Although, they are widely used in the study of conscious perception, ERPs are also employed across many areas of cognitive and sensory neuroscience (Del Cul, A; Baillet, S.; Dehaene, S., 2007; Koivisto & Revonsuo, 2010; Pitts et al., 2014). An ERP waveform (Figure. 1) comprises of a series of positive and negative voltage deflections, known as 'peaks' or 'components'. These components are denoted as 'P' for positive deflections and 'N' for negative deflections with respect to a reference electrode, followed by a number to show the sequence of occurring or the timing of peak (N2 refers to the second negative peak, N200 refers to a negative peak occurring 200 ms after stimulus onset). ERP components typically consist of an onset, a peak or plateau, and an offset. For example, the onset refers to the initial engagement of neural populations responding to a stimulus, whereas offset refers to a return to baseline activity (McWeeny & Norton, 2020). Early ERP components, such as P1 occurring around 100 ms after stimulus onset, are usually believed to represents the sensory-driven responses to the stimulus, because they are strongly affected by the physical stimulus properties (e.g. luminance) and can be evoked regardless of task demands (Koivisto & Revonsuo, 2010; Steven J. Luck, 2014). However, P1 wave can be altered by internal factors such as attention (Luck & Ford, 1998). Later ERP components are more likely to reflect higher-order (endogenous) cognitive events, as they depend more on internal states than on the physical characteristics of stimulus. For example, the P3 component, typically occurring around 300–400 ms after stimulus onset, represents endogenous component as it relies on factors such as task relevance, expectancy, and decision-making rather than stimulus properties alone (Donchin & Coles, 1988; Steven J. Luck, 2014).

Over the past three decades, research has shown the benefits of ERP approach on attention. Besides consciousness, which will be discussed below, much of this research has focused on visual modality. Spatial attention enhances the amplitudes of early ERP components such as P1 and N1, with stimuli presented at attended locations evoking larger amplitudes over posterior scalp regions compared to stimuli presented at unattended locations. These findings indicate that attention influences early sensory processing (Anllo-Vento et al., 1998; Luck &

Ford, 1998). The other attention related ERP component is selection negativity (SN), shows a sustained negative amplitude shift beginning around 200 ms after stimulus onset when attention is focused towards the task-relevant object features. SN gives the temporal measure of when specific stimulus features are selectively differentiated and processed in the brain (Luck & Ford, 1998). The N2pc (N2-posterior-contralateral) is also a negative attention-related component, occurring after 200 ms, observed over the posterior electrodes contralateral to the visual field containing the attended target. The N2pc describes the allocation and focussing of visual attention towards target stimuli (Eimer, 1996) and suppression of nearby distractors (Luck & Ford, 1998).

Despite extensive research on NCC, vision remains the most explored modality (Faivre et al., 2017). This is largely because of the well-established nature of the visual system, which allows for precise stimulus control (e.g. through visual masking), robust, and easily recorded cortical responses, and relatively consistent electrophysiological markers of conscious perception (Faivre et al., 2017). Other modalities including auditory, somatosensory, and multisensory perception, have only more recently started to receive more attention in consciousness research (Bekinschtein et al., 2009; Filimonov et al., 2022; Fisch et al., 2009; Orłowski & Bola, 2023; Snyder et al., 2015)

1.2 Main NCC candidates in visual and auditory awareness: VAN, AAN, and LP

Comprehending the neural correlates of consciousness (NCC) for vision and hearing demands the detection of electrophysiological markers that reliably distinguish between aware and unaware events. The Visual Awareness Negativity (VAN), Auditory Awareness Negativity (AAN) and Late Positivity (LP) have gained the most attention, as they represent the stages of early and late conscious processing.

Research has identified two potential neural correlates for visual awareness. Visual Awareness Negativity (VAN) is observed as a negative ERP amplitude difference between aware and unaware trials, measured around 150-350 ms after stimulus presentation (occurring in a range of N1 and N2), and is more prominent over temporal and occipital areas (Derda et al., 2019; Förster et al., 2020; Hurme et al., 2017) (Figure. 1).

Late Positivity (LP) occurs later, measuring around 250-600 ms post stimulus interval (P3 time window) as a difference wave, and is considered a late-stage marker of conscious processing. While P3 itself can be further divided into two subcomponents, an earlier frontocentral component (P3a), indicates automatic, stimulus-evoked attentional processes, which can occur even in unconscious states. A later parietally maximal component (P3b), linked to processes such as working memory updating, stimulus classification, and contextual updating (Chennu & Bekinschtein, 2012; Polich, 2007).

The occipito-temporal and parieto-central scalp distribution of VAN and LP can be seen in (Figure. 2).

In experimental settings like ‘oddball’ task, where participants detect rare or unusual targets, P3b is typically elicited only by rare, detected stimuli and not by frequently presented stimuli, even when these are consciously perceived. This raises questions about whether P3b is a true NCC, which should be elicited by all consciously perceived stimuli, not for rare ones only.

For VAN, the amplitude is more negative for aware stimuli compared to unaware stimuli, whereas for LP, the amplitude is more positive for aware stimuli compared to unaware stimuli (Eklund & Wiens, 2018). Evidence for one or both components can be observed using multiple experimental approaches to study visual awareness. For example, masking paradigms, a commonly used method, presenting a mask shortly after a stimulus can render it consciously available or unavailable mask shortly after it, depending on a different time intervals between them (Breitmeyer, 2007), attentional blink is seen in rapid sequence of visual stimuli, when two targets are presented among distractors (Martens & Wyble, 2010; Raymond et al., n.d.). Change blindness indicates a difficulty in detecting changes between two consecutive display of images, which are separated by a transient blink, or other interruption (Rensink, 1997; Simons & Rensink, 2005). Near-threshold stimuli are used to make the visual inputs close to the threshold of awareness, allowing ERPs to be compared for identical or near-identical stimuli when they are consciously perceived versus when they are not (Ojanen, V.; Revonsuo, A.; Sams, M, 2003). Bistable perception refers to a phenomenon when a single, unchanging visual stimulus can be interpreted in more than one way (Rodríguez Martínez & Castillo Parra, 2018). Common examples of bistable perception include binocular rivalry (Kaernbach et al., 1999) and Necker cube (Jürgen Kornmeier, Michael Bach, 2004). Current theories differ regarding the functional significance of VAN and LP in the domain of visual awareness.

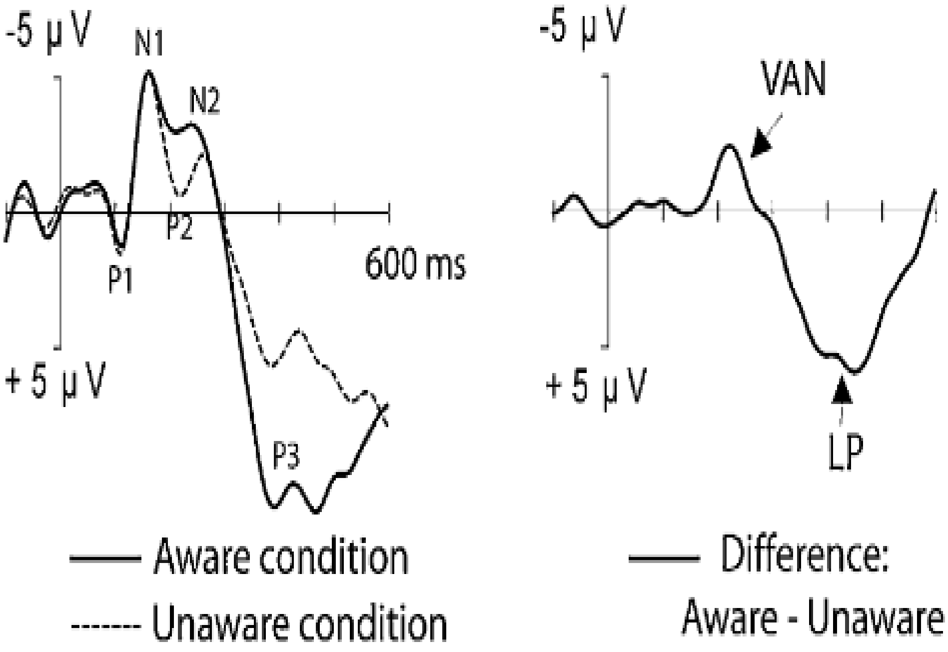

Figure 1 Left: ERPs recorded over occipital sites in relation to visual stimuli were averaged individually for aware trials and for unaware trials. Right: A difference wave was obtained by subtracting ERP responses to unaware trials from those to aware trials. The difference wave shows that awareness is related with a negative amplitude amplification occurring around 200 ms after the onset of stimulus (called visual awareness negativity VAN). This effect is accompanied by a positive amplification occurring around 300 ms (called late positivity). (The waves were recalculated from the data of Koivisto & Revensuo, 2003) (Koivisto & Revonsuo, 2010)

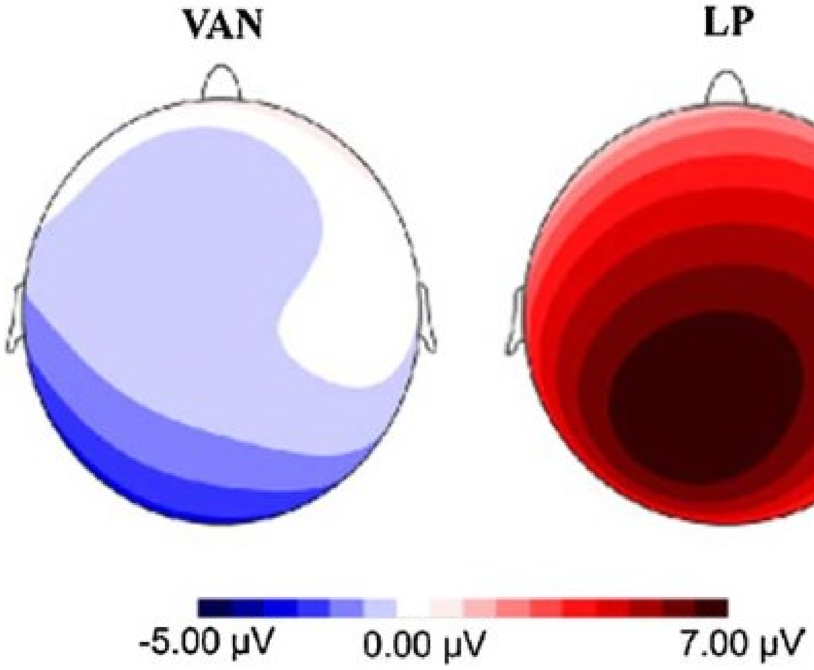

Figure 2 Scalp distribution (µV) of VAN and LP. These maps were obtained from aware and unaware difference waves in a condition (Koivisto et al., 2005)

As reported by recurrent processing theory (Lamme, 2010; Lamme & Roelfsema, 2000), local recurrent feedback within sensory areas (local recurrent processing) enables phenomenal consciousness, which refers to the qualitative, and subjective experience itself. Feedback processing between sensory and fronto-parietal areas (global recurrent processing) supports access consciousness, which enables reportability and cognitive access to perceptual content (Block, 2005). Following this theory, Visual Awareness Negativity (VAN) reflects local recurrent processing and thus index phenomenal consciousness, whereas the late positivity (LP) reflects global recurrent processing and index access consciousness (Andersen, L. M.; Pedersen, M. N.; Sandberg, K.; Overgaard, M., 2016; Koch et al., 2016; Koivisto & Grassini, 2016).

In contrast, Global Neuronal Workspace Theory (GNWT) proposes that VAN does not constitute a neural correlate of conscious awareness but represents unconscious sensory processing (Dehaene et al., 2006). In this view, conscious visual perception arises when stimulus related activity is globally broadcast through activation of fronto-parietal cortex, which is indexed by the LP (Dehaene & Changeux, 2011). Consequently, supporters of Recurrent Processing Theory argue that VAN should serve as a reliable indicator of visual awareness, while supporters of Global Neuronal Workspace Theory argue that VAN merely represents a preconscious prerequisite for global workspace activation and does not itself correlate with conscious awareness (Lamy et al., 2009).

In support of the early model, prior studies found that VAN is related to visual awareness (Koivisto & Revonsuo, 2010). The early model of consciousness proposes that conscious awareness emerges from early, local recurrent processing within sensory cortices and is indexed by early ERP components such as the Visual Awareness Negativity (VAN), rather than the late post-perceptual components like Late Positivity (LP). However, many of these studies relied only on subjective measures to assess awareness, making them prone to potential confounds arising from individual differences in task performance (Lamy et al., 2009). When awareness is defined using objective performance measures, aware trials are typically correct trials, whereas unaware trials are more likely to be incorrect. This association between awareness and accuracy may obscure the influence of awareness by conflating it with performance-related processes.

Following this logic, two latest studies that regulated for performance questioned whether VAN truly represents the earliest correlate of visual awareness (Lamy et al., 2009; Salti et al., 2012). In these studies, only correctly localized trials were considered and categorized as aware and unaware based on subjective reports. In Lamy et al., 2009 study, participants were shown backward-masked line segments and participants reported both the location of the target and their subjective experience with two responses (i.e., whether they had seen the stimulus or were guessing). Even the performance of guessing trial emerges above chance level due to a mix of lucky guesses and unconscious processing, ERP from unaware incorrect trials were used to measure chance-level activity. Subtracting this chance-related ERP from the aware correct ERPs should capture isolated neural activity related to conscious processing. Results showed a larger P3 (LP) for aware correct trials, but no differences in earlier components (N1, N2, P1 or P2), providing evidence that LP, not VAN reflects visual awareness. This approach is consistent with Global Neuronal Workspace Theory, which considers consciousness in terms of reportability, hence equating correct trialswith conscious awareness. However, no-report paradigms have been developed to study consciousness independently of overt behavioural response.

Salti et al.(2012), used the same approach as Lamy et al.(2009) but extended it by controlling for both confidence and performance. Participants rated their awareness using three levels scale: clearly seen, unsure, and sure they had not seen the target. No evidence was found for VAN, and the authors concluded that LP represents the earliest neural correlate of visual awareness.

On the contrary, Koivisto & Grassini (2016) proposed that because of various reasons VAN was not detected in previous studies: (1) small stimulus sizes may have elicited only small neural populations, (2) backward masking may have produced overlapping neural responses to the target and the mask; (3) combining ipsilateral and contralateral responses may have decreased sensitivity, as VAN is presumed to be strongest over the hemisphere contralateral to stimulated visual field (Koivisto & Revonsuo, 2010). Furthermore, findings from no-report paradigms shows the presence of conscious perception without task demands or direct reports, with conscious processing observed without a corresponding LP, suggesting that LP may reflect post-perceptual or report-related processes rather than consciousness itself.

To counter these problems, Koivisto & Grassini (2016) used larger stimulus sizes presented at low contrast instead of backward masking, and contralateral and ipsilateral electrodes were evaluated separately. They reported both VAN and LP, and proposed that VAN, not LP is the earliest neural correlate of visual awareness.

In conjunction with VAN in the visual domain, an Auditory Awareness Negativity (AAN) has been observed in auditory modality. Like VAN, AAN is characterized by a negative amplitude difference between aware and unaware trials, measured around 200 – 300 ms after stimulus over parietal and temporal scalp areas (Eklund & Wiens, 2019). Cross study analyses show similarities between visual and auditory awareness, including the presence of early negative and late positive difference waves across modalities (Dykstra et al., 2017). The late positive component of auditory awareness represents higher cognitive processing related to consciously perceived sounds and is considered analogous to the P3b component observed in visual awareness. Topographically, VAN is maximal over the posterior scalp regions (Koivisto & Grassini, 2016), whereas AAN is maximal over the anterior scalp areas (Eklund & Wiens, 2019). Moreover, the amplitude of VAN is strongest over the regions contralateral to the eliciting stimulus, while this effect is weaker or absent for AAN (Eklund et al., 2021; Eklund & Wiens, 2018; Harris, 2018; Koivisto & Grassini, 2016; Königs, Liane; Gutschalk, Alexander, 2012).

In electrophysiological studies of awareness, visual perception has been explored more as compared to auditory perception. An early study in hearing employed a detection task in which participants identified tones presented at their detection threshold (Hillyard, Steven A.; Squires, Kenneth C.; Bauer, J. W.; Lindsay, P. H., 1971). Participants were required to detect tones embedded in white noise, with a 50% chance of tone occurrence. Central electrode (vertex) was used for EEG recording, referenced to the right mastoid. ERPs were averaged separately for detected tones (hits) and undetected tones (misses). Detected tones elicited an N1 component in one participant and a P3 component in all three participants, whereas undetected tones produced essentially flat ERPs. These results were later reproduced and expanded with more participants in other additional studies (Parasuraman & Beatty, 1980; Paul, D. D.; Sutton, Samuel, 1972; Squires, Kenneth C.; Hillyard, Steven A.; Lindsay, Peter H., 1973).

In Paul and Sutton (1972), EEG was recorded from the vertex while tones were presented at threshold, and response criteria were manipulated either through payoff structure or by changing the number of trials. The results showed that N1 amplitude was unchanged by a response criterion changes, whereas P3 amplitude for detected tones was reduced when participants adopted a low detection threshold compared to a high detection threshold. With high detection threshold, participants reported that they detected a tone when they are confident that they heard it. Thus, suggesting that P3 reflect post perceptual or decisional processes rather than sensory awareness.

In a second study (Squires, Kenneth C.; Hillyard, Steven A.; Lindsay, Peter H., 1973), EEG was recorded from the vertex while tones were played at a detection threshold, and participants rated their confidence in detection. The results showed that both N1 and P3 components were larger in amplitude and shorter in latency for tones detected with high confidence compared to those detected with low confidence. The authors proposed that N1 is associated with the perceived strength of a sensory signal, aligned with signal detection theory (Macmillan, Neil A.; Creelman, C. Douglas, 2005). Although the physical properties of signal is same across the trials, the perceived signal strength varied, and both N1 amplitude and latency were associated with tone intensity (Picton, Trevor W.; Woods, David L.; Braun, Michael; Healey, T. M. J., 1977). In passive listening tasks with different tone intensities, N1 becomes larger and earlier as the tone intensity increases. Notably, in the active detection task, tones detected with the highest confidence produced N1 amplitude and latency similar to those produced by 8 dB louder tones in the passive task, indicating N1 reflects internal perceptual strength rather than physical stimulus intensity alone.

In a third study (Parasuraman & Beatty, 1980), EEG was recorded with central electrodes, while tones of different frequencies presented at the detection threshold. Participants were asked to not only detect the tone but also differentiate the frequency of the tone. Results indicated that, regardless of the pitch, tones detected with high confidence produced larger N1 and P3 components than tones detected with low confidence. Furthermore, correctly detected and correctly identified tones produced larger P3 amplitudes compared to those that were incorrectly identified. In line with earlier studies (Paul, D. D.; Sutton, Samuel, 1972; Squires, Kenneth C.; Hillyard, Steven A.; Lindsay, Peter H., 1973), P3 amplitude indicate detection confidence and post-perceptual decision processes, whereas N1 is not being affected by identification accuracy, it may be associated with the perceived signal strength.

In a recent study, an informational masking task was used to study the neural correlates of auditory awareness (Gutschalk et al., 2008). In this study, multiple non-target tones with random frequencies in background were played along with a sequence of target tone. This “background cloud” of tones produced informational masking, affecting the target sequence detection (multitone masking). To prevent physical masking, the frequencies of target tones were distinct from those of the non-target tones. Participants were instructed to press the button as soon as they detected the target sequence, while MEG was used to measure the neural activity, and it showed that detected target tones elicited an awareness-related negativity between 50 – 250 ms after tone onset, whereas undetected tones did not, providing evidence for an early auditory correlate of conscious perception .

In another study (Bekinschtein et al., 2009), an auditory oddball paradigm was used to examine hierarchical processing in auditory awareness. Participants were instructed to hear five sounds: the first four sounds were similar, while the fifth sound could match (local standard) or differ (local deviant: elicit early automatic responses without conscious attention produced a mismatch negativity MMN at 100-200 ms) from them. At a higher level, most sound sequences followed the same overall pattern (global standard), whereas rarely a sequence was violated (global deviant), global deviants elicited a P3 like response between 300-600 ms, associated with the conscious detection of sequence violation. This study proposed two stage processing model of auditory awareness, comprising early automatic detection followed by later conscious detection of higher order patterns.

An awareness-related negativity was further reproduced by (Dykstra & Gutschalk, 2015), who studied the effect of awareness on mismatch negativity (MMN). In their study, ERPs to frequent standard tones were subtracted from the ERPs to rare deviant tones to measure the mismatch negativity (MMN) (Szychowska, Malina et al., 2017; Wiens, Stefan, Szychowska, Malina, et al., 2019; Wiens, Stefan, van Berlekom, Erik, et al., 2019). A multitone masked stream of target tones, comprising both standard and deviant tones, was used to modify awareness (Dykstra & Gutschalk, 2015). The participants were instructed to press the button as soon as the stream of target tones are detected. Awareness-related negativity was elicited by detected tones, whereas undetected tones did not produce it. Moreover, deviant target tones produced larger negativity than standard target tones, and MMN was only found for the detected tones, suggesting that auditory awareness influences early neural responses to deviant sounds.

In a pioneering study by (Eklund & Wiens, 2019), an auditory threshold detection task was used to investigate the neural correlates of auditory awareness. Participants were instructed to listen tones at their individual perceptual threshold while EEG was recorded and reported on whether they were aware of each tone. When comparing ERPs for aware versus unaware tones, the authors observed an early negative difference around 200 ms post-stimulus onset, called Auditory Awareness Negativity (AAN), and a later positive difference around 300 ms, corresponding to Late Positivity (LP).

In a recent study by (Filimonov, Revonsuo, Koivisto & Krabbe, 2024), the role of feature-based attention and response requirements on auditory awareness-related ERPs was explored using a GO/NOGO design combined with subjective awareness ratings. This design allowed the authors to separate awareness, attention, and response requirements within the same experiment. They found that AAN was prolonged for aware trials and was not reliably influenced by either attention or response requirement, showing it reflects auditory awareness. Conversely, LP was influenced by both attention and response demands, suggesting its role in post-perceptual processing rather than in awareness.

Comparing the trials directly when a sound is consciously perceived with the trials in which it is not, currently considered the most reliable method to detect the auditory NCC. More complex experimental conditions such as bistable perception, oddball tasks, or change detection, involve higher cognitive processes, like attention, working memory, and decision making, which can affect the isolation of neural activity that specifically reflects conscious perception itself.

AAN and VAN can fall under a broader category called Perceptual Awareness Negativity (PAN) (Dembski et al., 2021,Eklund & Wiens, 2019; Filimonov et al., 2024). VAN and AAN share a remarkable similarity in latency, polarity, and lateralization, suggesting that common neural processes contribute to conscious perception across sensory modalities. Their scalp topographies are different, VAN is maximal over posterior electrodes indicating activity in visual cortical areas, whereas AAN is maximal over the anterior-lateral electrodes, indicating neural activity in auditory cortical areas. This difference of scalp locations indicate the modality-specific sensory areas from which these signals originate. Notably, the spatial and temporal characteristics of these components can shift according to the stimulus and task complexity (Mathewson et al., 2009).

Evidence from clinical studies further supports the role of PAN in early sensory awareness. Patients with right brain hemisphere damage are unable to perceive stimuli in left visual and auditory fields, accompanied by the reduction or absence of both VAN and AAN. These neural signals can reappear or normalize when perceptual abilities recover (Heikki Hämäläinen et al., 2014) . Together, these findings suggest VAN and AAN act as a modality specific electrophysiological marker of early sensory consciousness, appearing around 120-200 ms after stimulus onset.

The characterization of PAN indicates that shared neural processes may underlie conscious perception across sensory systems, with each modality involving its respective cortical regions but sharing a common functional structure. This gives an idea that the early onset of conscious awareness indicates generalized patterns of neural circuit activity across sensory domains. However, it is important to distinguish PAN from other co-occurring neural processes, like occurrence of attention or response selection that may happen at the same time before or after awareness (Aru et al., 2012). These neural processes can partially coincide temporally and spatially with electrophysiological markers of awareness, making it hard to distinguish which components genuinely reflects consciousness and which reflect higher cognitive functions. To recognize the physiological mechanisms underlying PAN, future research using both non-invasive EEG and MEG with invasive recordings in animal models and human patients undergoing neurosurgical processes may help in identifying the circuit level and cellular mechanisms that give rise to PAN (Aru et al., 2020; Rutiku & Bachmann Talis, 2017; Siegle et al., 2021). Such approaches may also explain how early sensory signals interact with later occurring perceptual and decision related processes.

The studies have been done to explore PAN (Eklund & Wiens, 2019, 2020, 2022; Filimonov et al., 2022, 2024a, 2024b, 2025; Koivisto & Grassini, 2016b) as a neural correlate of consciousness (NCC), while also investigating LP as a component more closely related to attention and post perceptual processing. However, whether PAN can be fully disassociated other cognitive processes and thus qualify as NCC proper is still debatable (Koivisto & Grassini, 2016a; Polich, 2007).

1.3 ERP components in multimodal conditions

Studies on ERP correlates of consciousness have mainly focused on single sensory modalities. However, in everyday life, conscious perception is generally multimodal, representing a combined processing of inputs from different senses and giving rise to what has been termed as the ‘phenomenal unity of consciousness’ (Revonsuo, 1999) or ‘unified qualitative subjectivity’ (Searle, 2004). Notably, cross-modal interactions can affect conscious perception in both positive and negative ways (Pápai & Soto-Faraco, 2017). For example, when auditory and visual stimuli are incongruent, the detection of visual motion is worse compared to congruent conditions (Rosemann et al., 2017). Auditory stimuli can also modulate the temporal resolution of visual perception; for example, a single visual flash may be perceived as multiple flashes instead of one when accompanied by multiple sounds (Shimojo et al., 2001). This cross-modal interplay can occur unconsciously, and stimuli of one sensory modality can improve awareness of stimuli in other modality (Faivre et al., 2017). Multiple studies have been done that explored Perceptual Awareness Negativity (PAN) and Late Positivity (LP) as ERP correlates of consciousness, but there is less data regarding their role in multimodal conditions. Much of the existing research on perceptual awareness mainly progressed separately, focusing on a single perceptual modality at a time. However, our everyday experience is arguably multimodal (Filimonov et al., 2022).

In the present study, we aim to explore how Auditory and Visual Awareness Negativity (AAN and VAN) interact under multimodal conditions, and how the Late Positivity (LP) is modulated by response requirements. For this, we designed a GO/NO-GO experiment where both perceptual awareness and response requirements are manipulated through a sensory discrimination task. Participants are instructed either to respond to target stimuli or to withhold responses, depending on task instructions. Responding selectively to target stimuli requires feature-based attention, while responding to both target and non-target stimuli primarily reflects response-related processing. Including both aware and unaware stimuli in all the combinations, this design allows dissociation and comparison of electrophysiological correlates related to awareness, attention and response execution in both visual and auditory modalities. Since the project is still ongoing, experimental design and data collection is in progress, we focused on comparing visual and auditory NCC in the bimodal condition in unattended non-target trials.

Behavioural and ERP data will be analysed using linear-mixed effect models implemented in R using the lme4 package, with analyses focusing on established electrode clusters related with AAN, VAN, and LP.

1.4 Research hypotheses

The broader project intended to differentiate the neural mechanisms underlying perceptual awareness, attention and response requirements across auditory and visual modalities within multimodal GO/NOGO paradigm. Due to the ongoing nature of the project and availability of limited data the current study addresses only subset of original aims. Accordingly, the present study had the following specific aims:

1) To examine whether AAN and VAN reflect differences between aware and unaware stimuli under bimodal conditions.

2) To examine differences in timing and scalp distribution of AAN and VAN across auditory and visual modalities.

3) To examine whether LP is affected by awareness in the absence of overt response requirements.

The main hypotheses are:

H1: Visual awareness will increase VAN over the posterior scalp regions, reflecting early sensory processing.

H2: Auditory awareness will increase AAN over the fronto-central scalp regions.

H3: LP will not reliably distinguish between aware and unaware non-target trials, reflecting its role in post perceptual task related processing rather than awareness itself.

2 Methods

This study adopted an experimental design to explore the underlying cognitive mechanisms of attention, awareness and response requirement under multimodal conditions. EEG signals were used to analyse neural responses to the visual and auditory stimuli.

2.1 Participants

The study consists of 18 participants recruited from the Turku area. The participants had given their informed consent in accordance with the Declaration of Helsinki, before taking part in the experiment. Ethics Committee for Human Sciences at the University of Turku also accepted this study. All the participants were healthy right-handed individuals aged 18-35 years, with normal or corrected-to-normal vision and with normal hearing, and no history of neurological or psychological disorders. Exclusion criteria included failure to calibrate individual auditory and visual thresholds within a 30-70% stimulus detection rate, non-adherence to task instructions, or excessively noisy EEG data (i.e., containing many artifacts across most electrodes both before and after preprocessing). Two participants were excluded based on these criteria, resulting in a final sample size of N = 16.

2.2 EEG Recording

EEG signals were recorded from 64 Ag/AgCl sintered ring electrodes arranged on a recording cap (Easycap GmbH, Germany) and amplified using a NeurOne system (Mega Electronics Ltd). Signals were recorded with a bandpass filter of 0.05-100 Hz and a sampling rate of 500 Hz. EEG data were initially referenced to the Fz electrode and later re-referenced to the common average during preprocessing.

2.3 Stimulus Presentation

The stimuli consisted of three near-threshold visual stimuli (circle, triangle and square) and three near-threshold auditory stimuli (‘do’, ‘la’, ‘sol’) presented at high, medium, and low pitches. Visual stimuli were presented on a VIEWpixx/EEG LCD monitor (resolution: 1920 × 1080; refresh rate: 120Hz). Auditory stimuli were delivered binaurally via in-ear earphones (Neuroscan, 10-ohm, ¼ stereo) (Filimonov et al., 2022; Filimonov, Krabbe, et al., 2024). Logitech gamepad control (model F310) was used to record participant responses (Filimonov, Krabbe, et al., 2024). PsychoPy (3.0.7) was used for stimulus design and presentation on a Windows 10-based computer.

Trials could include a visual stimulus only, an auditory stimulus only, a simultaneous bimodal (visual + auditory) stimulus, or no stimulus (empty trials).

Before the main experiment, individual awareness thresholds were calibrated using a staircase procedure.

2.4 Study design

The experiment consisted of 12 experimental blocks, each containing 54 trials, including 14 target trials, 27 non-target trials, and 13 empty trials.

2.5 Procedure

The participant was seated comfortably in a room approximately 70 cm from the display. They were informed about the experimental procedure and instructed to keep their eyes open, minimize eye blinks, and avoid unnecessary movements during the experiment.

The experiment followed a GO/NO-GO design and consisted of 12 experimental blocks. In GO blocks, participants were instructed to respond only to a predefined target stimulus, which changed in each block and the order was counterbalanced. In NO-GO blocks, participants were instructed to respond to all other stimuli except target stimulus of the same modality. The order of GO and NO-GO blocks were counterbalanced across participants.

The trial began with a blank grey screen presented for 200 ms, followed by a fixation cross presented at the centre of the screen for 300 ms. This was followed by a blank screen with variable duration of 500-700 ms. The stimulus (visual, auditory or bimodal (visual + auditory) was then presented for 400 ms, followed by a blank screen for 600 ms and a second fixation cross for 300 ms. There was 3000 ms time for the participant to respond with the button press according to the instructions.

In Go blocks, participants were instructed to press “X” button on the joystick if they detected the target stimulus. In the NO-GO blocks, participants were instructed to press the same button on the joystick if they detected any stimulus other than the target stimulus of the same modality. After responding, participants rated their perceptual awareness using the Perceptual

Awareness Scale (PAS)(Dong et al., 2015), which consists of three levels: clear perception, weak perception, and no perception.

Before the main experiment, there was an introductory phase which allowed the participants to familiarize themselves with the visual and auditory stimuli. This was followed by a calibration phase to measure individual awareness thresholds for all stimuli.

After the introductory phase, participants completed a calibration phase to measure their individual awareness thresholds for all stimuli. Each visual and auditory stimulus were presented separately. A single visual threshold and a single auditory threshold were calculated and subsequently applied to all visual and auditory stimuli, respectively. The calibration phase comprised of three interleaved one-up/one-down staircases for visual and auditory stimuli, using 3, 2, 1, 0.5, and 0.1 dB step sizes. The first calibration block comprised 250 trials. However, if all staircases reached five reversals before completion of block, the calibration block was terminated and followed by a validation phase.

In the validation phase, participants were instructed to report their perceptual awareness for both visual and auditory stimuli using the Perceptual Awareness Scale (PAS). The average of the last five reversals was calculated for each staircase. If the initial validation failed, the experimenter selected either one of the two estimated thresholds or their average, based on visual inspection of the staircase data and the quality of threshold convergence.

A second validation block was then started. If this validation also failed, a second calibration block comprising of 50 trials was conducted to ensure accurate estimation of the awareness threshold before the main experiment.

2.6 Analysis

EEG data were pre-processed using EEGLAB (Delorme & Makeig, 2004) (version, 2024.0) and MATLAB (R2025b). Raw EEG data were inspected to verify that all channels were correctly labelled, and the recordings were of good quality. The detection for automated bad channels was performed using EEGLAB function ‘pop_rejchan’, based on kurtosis, joint probability, and spectral criteria with a 4 standard deviation threshold. This step identifies electrodes that exhibit abnormal signal characteristics, which may result from poor electrode-scalp contact (due to insufficient gel or participant movement) or continuous electrical noise, making their signals unreliable.

A 0.5 Hz high-pass filter (FIR (finite impulse response), Hamming window; transition bandwidth 1Hz; filter order, 1650)was applied to remove the slow voltage changes unrelated to neural activity, such as those caused by gradual changes in electrode-scalp contact or physiological shifts. Removing these slow changes from signals improve baseline stability and helps more accurate separation of neural and non-neural sources(blinks and muscle movements) during Independent Component Analysis (ICA). When these slow changes in signals removed from the data, it becomes more clearer, and ICA can differentiate between signal sources more correctly. This is recommended for ERP research because ERPs rely on clear and consistent baselines across trials.

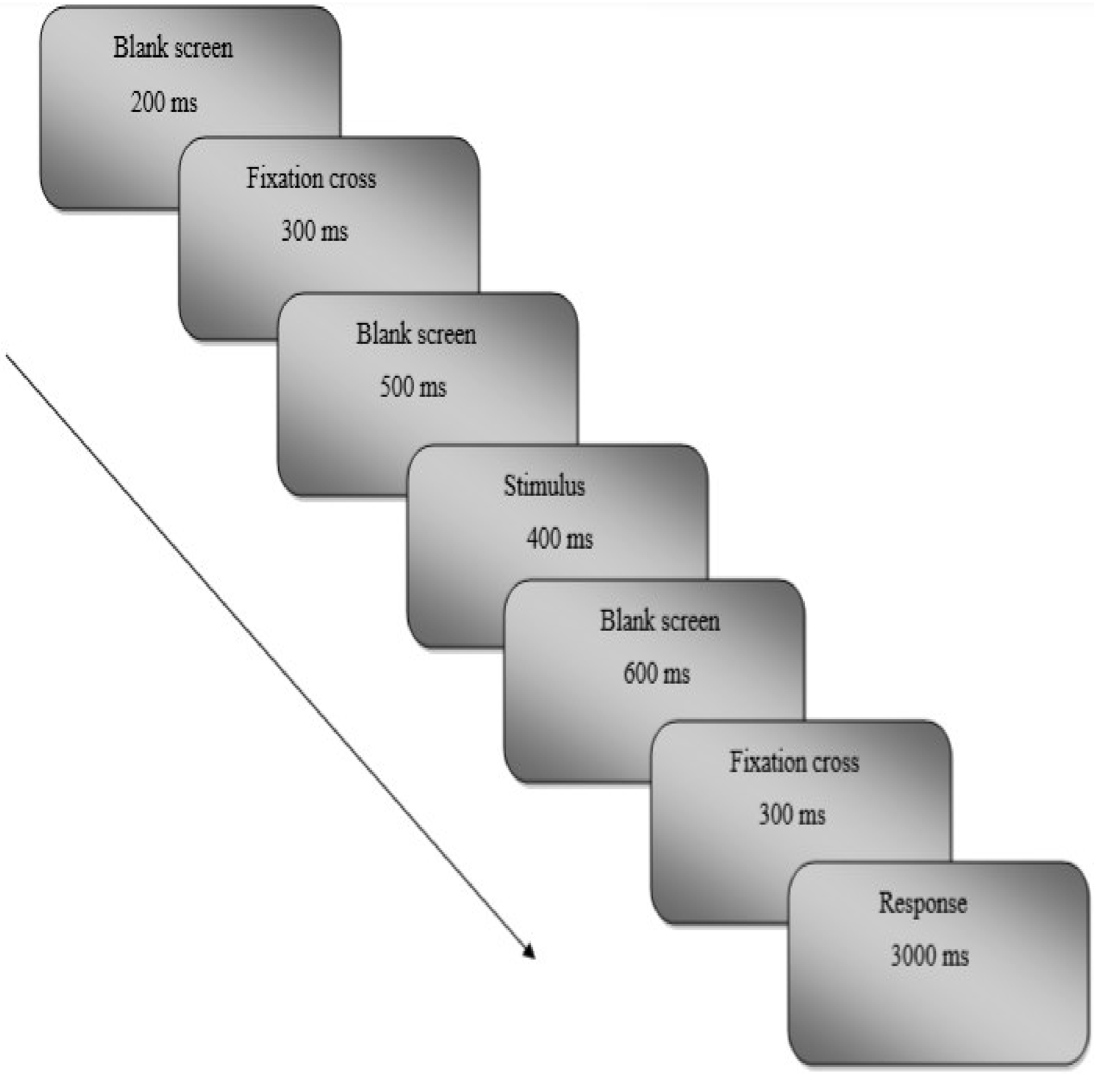

Figure 3 Trial structure

(Tanner et al., 2015; Zhang et al., 2024). After filtering, remaining noisy channels were removed by visual inspection.

Line noise at 50 Hz was attenuated using the EEGLAB function ‘pop_cleanline’, which removes electrical interference without affecting the EEG signals. Subsequently, a 30 Hz low-pass filter (FIR, Hamming windowed; transition bandwidth, 6.7 Hz; filter order; 247) was applied to the data before epoching. This filtering step is commonly used in ERP studies to decreases high-frequency muscle activity while retaining the low-frequency neural signals necessary for ERP analysis.

After filtering, the data were segmented into epochs. Independent Component Analysis (ICA) was performed, and components identified as artefactual using the ICLabel plugin (Pion-Tonachini et al., 2019) (version 1.4.). ICLabel classifies components into categories such as brain, eye movements, muscular activity, or noise. Components classified as non-brain were removed only when their artefactual nature was confirmed by inspection of scalp topographies, power spectra, and time-course characteristics.

Removed channels were restored using EEGLAB’s spherical interpolation function ‘pop_interp’. Across participants, 5 to 15 electrodes were interpolated. The data were then baseline-corrected using a -200 to 0 ms interval and re-referenced to link mastoids.

Further ERP analyses were done with MATLAB (version, R2025b). The three level PAS scores were collapsed into two categories, the levels ‘clear perception’ and ‘weak perception’ were merged into single category called ‘aware’, while ‘no perception’ was placed in ‘unaware’ category. We implemented an Amplitude ~ Awareness + (1|id) linear mixed effects model with awareness as a fixed effect. We compared the models using Akaike Information Criterion (AIC), and selected the model with minimal AIC values, without random intercepts. To model Auditory Awareness Negativity (AAN), mean amplitude were extracted from a 200-300 ms time window across an electrode cluster used in many AAN studies, included, ‘Cz’, ‘Pz’, ‘Fz’, ‘F1’, ‘F2’, ‘FC1’, ‘FC2’, ‘C1’, ‘C2’, ‘CPz’, ‘CP1’, ‘CP2’, ‘C3’, ‘C4’, ‘FC3’, ‘FC4’, ‘F3’, ‘F4’, ‘CP3’, and ‘CP4’ electrodes (Dembski et al., 2021; Eklund et al., 2020; Eklund & Wiens, 2019; Filimonov, et al., 2024, 2024). The predefined time window for auditory Late Positivity (LP) was 400-600 ms, and the same electrode cluster as for the AAN used.

To model Visual Awareness Negativity (VAN), mean amplitude were extracted from a 200-300 ms time window across a posterior electrode cluster ‘O1’, ‘O2’, ‘PO3’, ’PO4’, ‘PO7’, ‘PO8’, ‘Pz’, ‘P3’, ‘P4’, ‘POz’, ‘CPz’, ‘CP1’, ‘CP2’ commonly reported in VAN studies (Filimonov et al., 2022; Koivisto & Grassini, 2016; Koivisto & Revonsuo, 2010; Railo et al., 2011). The predefined time window for visual Late Positivity (LP) was 400-600 ms and used the same electrode cluster as for auditory LP.

3 Results

ERPs were computed for 16 participants. Grand average ERPs from Cz electrode for auditory condition are shown in Figure 4 and for visual condition in Figure 5. The difference wave in auditory condition shows a negative peak at 150-250 ms and a large, sustained positive peak at 650-800 ms. In contrast, the difference wave for visual condition shows a negative peak at 220-300 ms and a positive peak at 350-450 ms. The timing of these components indicates early awareness related activity: AAN for the auditory condition and VAN for the visual condition, reflecting early stages of conscious processing. There is no typical LP in the auditory condition, whereas the visual condition shows a typical LP component, indicating late stages of conscious processing.

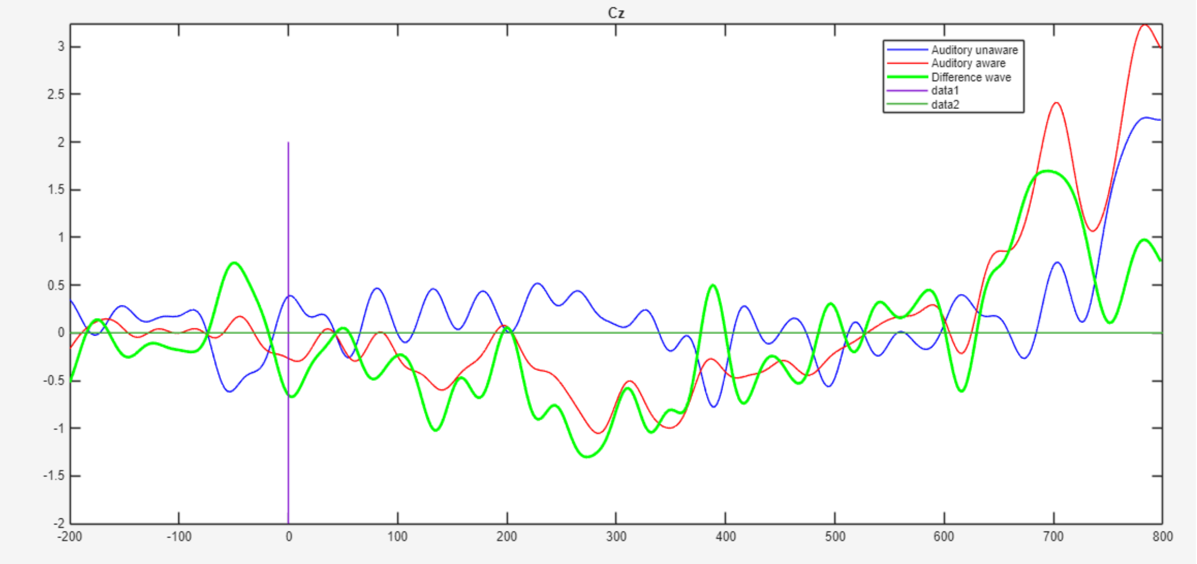

Figure 4 ERP amplitudes of auditory aware and unaware trials over the Cz electrode

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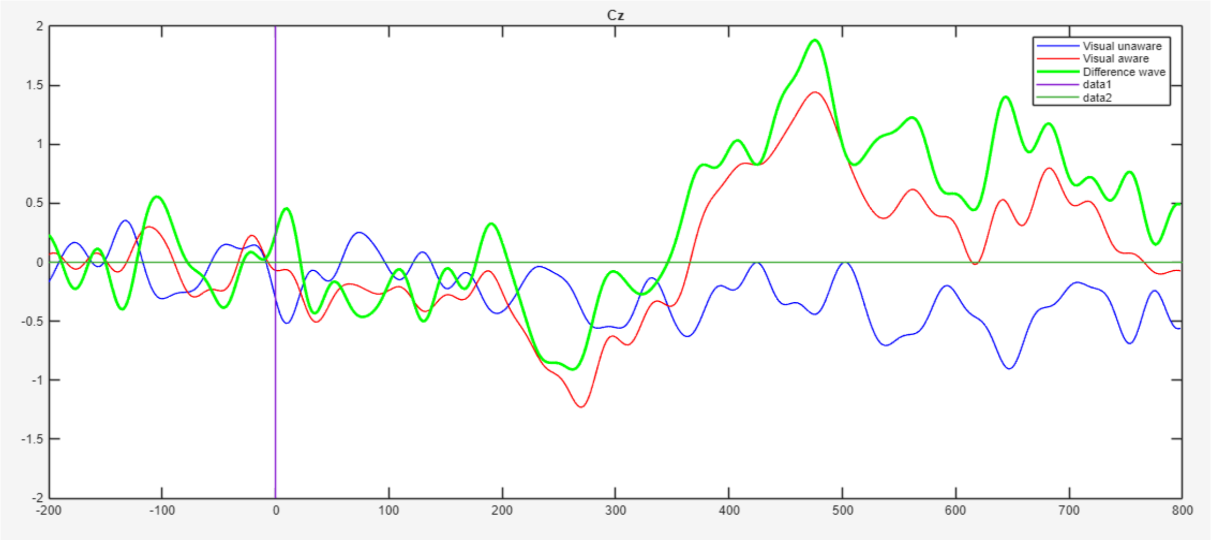

Figure 5 ERP amplitudes of visual aware and unaware trials over the Cz electrode

The results of the scalp topographies of the auditory and visual conditions are shown in Figure 6 and Figure 7, respectively. In the auditory condition a small, scattered activation is observed around 100 ms over parietal and temporal areas, which becomes more centralized around 300 ms, followed by a strong centro-parietal activity around 500-800 ms. In visual condition, a small posterior activation appears around 100 ms, with central-parietal activity appearing between 250-400 ms..

Figure 6 Scalp topography map for auditory condition

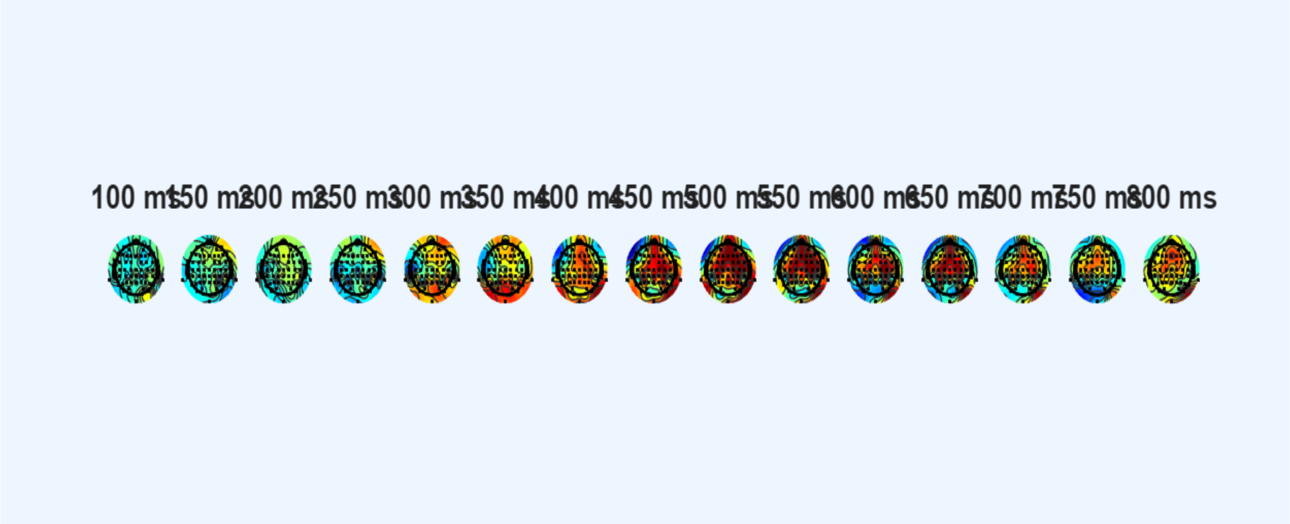

Figure 7 Scalp topography map for visual condition

The linear mixed effect model in the AAN time window showed a significant effect of awareness, with higher amplitudes in aware trials compared to unaware trials, SE = 0.307, t(1417) = -2.48, p = 0.013, 95% CI [-1.36, -0.16]. The model without random intercepts, selected based on the minimal AIC, showed a residual standard deviation of 5.70 µV, indicating trial-to-trial variability.

The linear mixed effect model for the VAN showed a significant difference between aware and unaware trials, with lower amplitudes in aware trials, SE = 0.273, t(1726) = -2.30, p = 0.02, 95% CI [-1.16, -0.09], and a residual standard deviation of 5.65 µV.

In the auditory LP time window, the model showed a significant effect of awareness with lower amplitude in aware trials, SE = 0.293, t(1417) = -3.14, p = 0.001, 95% CI [-1.49, -0.34] and a residual standard deviation of 5.42 µV. Similarly, for the visual LP, there was a significant effect of awareness, with lower amplitude in aware trials, SE = 0.27, t(1726) = 2.63, p = 0.008, 95% CI [0.18, 1.27], and a residual standard deviation of 5.74 µV.

4 Discussion

The purpose of this study was to compare the auditory and visual electrophysiological markers of consciousness in bimodal conditions. By emphasizing specifically unattended, non-target trials, the analyses were designed to investigate neural activity related to perceptual awareness while reducing response related confounds. Overall, the results show that early modality-specific ERP components Auditory Awareness Negativity (AAN) and Visual Awareness Negativity (VAN), reliably distinguished aware from unaware stimuli, while Late Positivity (LP) were less consistent and more variable. This pattern points to a functional dissociation between early neural markers of perceptual awareness and later components related to post perceptual cognitive processes (Koivisto & Revonsuo, 2010; Railo et al., 2011).

Within visual modality, VAN was observed as an enhanced negative deflection over posterior scalp regions for consciously perceived stimuli. This finding is consistent with prior studies linking VAN with early visual awareness and recurrent processing within visual cortical areas (Koivisto et al, 2009; Koivisto & Revonsuo, 2010). The presence of VAN under bimodal conditions indicates that early awareness-related visual processing can occur independently of explicit attentional focus (Pitts et al, 2014).

Within auditory modality, AAN consistently differentiated aware from unaware stimuli and showed a fronto-central scalp distribution. Prior studies have also identified AAN as an auditory counterpart of VAN, indicating early conscious processing of auditory information (Eklund & Wiens, 2018; Chennu et al, 2016). Although AAN and VAN are often considered as modality-specific forms of Perceptual Awareness Negativity, the differences in the timing and topography of AAN and VAN suggests fundamental differences in auditory and visual sensory processing. These results suggest that conscious perception happens within specific sensory systems, rather than via a single general mechanism at early processing stages (Lamme, 2006).

In contrast to the consistent effects of AAN and VAN, LP effects were less consistent across conditions and modalities. There were some evident differences between aware and unaware trials were present, but their timing and magnitude varied, especially in the auditory modality. LP is often associated with post-perceptual processes such as stimulus evaluation, decision making, and task relevance (Dehaene & Changeux, 2011; Pitts et al, 2014). The variability of

LP effects observed in this study indicates that this component is heavily influenced by task-related factors, even without explicit responses, suggesting it is not a direct neural marker of conscious perception.

The dissociation between early awareness-related components and later LP effects has important implications for theories of consciousness. The current findings align more closely with Recurrent Processing Theory (RPT), which proposes that conscious perception arises from recurrent activity within sensory cortices without requiring late, global neural ignition (Lamme, 2006; Lamme & Roelfsema, 2000). On the other hand, Global Neuronal Workspace Theory (GNWT) proposes that conscious perception involves a strong late positivity, reflecting widespread neural activity across fronto-parietal networks (Dehaene et al, 2006; Dehaene & Changeux, 2011). The lack of consistent LP effects observed in our study challenge this view, suggesting that late neural activity indicates post-perceptual cognitive processes rather than awareness itself.

A few limitations of this study should be considered. First, the relatively small sample size may have reduced statistical power, specifically identifying later ERP component such as the LP. Second, the long duration of the experimental protocol could have caused fatigue or fluctuations in attention, affecting the neural responses. Third, this thesis examined only the subset of original project aims, conclusions about attention and response selection are limited. Future studies should use fully crossed experimental design to investigate these factors and to better differentiate the role of perceptual awareness, attention, and task demands (Pitts et al, 2018).

Despite these limitations, the present study contributes to the growing evidence for early, modality-specific neural correlates of conscious perception. The reliable differentiation of aware versus unaware stimuli by AAN and VAN across bimodal conditions supports early sensory markers of awareness. Furthermore, the separation of early ERP components from later LP effects highlights the importance of distinguishing perceptual awareness from later cognitive and task-related processes in consciousness research.

5 Conclusion

Overall, this study showed AAN and VAN as an early correlate of conscious processing while LP as a late correlate of consciousness associated with higher cognitive processing. These findings increase our understanding of spatial and temporal dynamics of awareness across auditory and visual modality in bimodal conditions.

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