Exploring the Shared and Distinct Neural Substrates Associated with Lapses of Auditory and Visual Sustained Attention

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Layman's summary

The ability to sustain your attention or remain alert is becoming increasingly important in everyday life, ranging from driving a car and remaining alert to when the car in front brakes, to work environments that require employees to continuously attend and monitor automated systems for long periods of time. However, our ability to sustain attention can fluctuate over time, and lapses of sustained attention can have serious consequences, such as drops in attention leading to road accidents. Also, attentional deficits are central to a number of psychiatric disorders, such as attention-deficit hyperactivity-disorder (ADHD) and schizophrenia. As such, there is growing scientific and practical importance in having the ability to predict lapses of sustained attention before the lapse occurs using signals from the brain. Previous research has shown that lapses in visual sustained attention is associated with reduced frontal P3 amplitudes before a lapse occurs. Researchers have suggested these findings indicate that the frontal P3 is a neural mechanism that reflects endogenous (top-down/higher order) attentional processing that can track the timing structure of the task. However, no study to date has examined the brain signals that may show predictive characteristics of lapses in auditory sustained attention. This study examined the electrical signals from the brain that may predict lapses of auditory and visual sustained attention. Specifically, this study examined whether lapses of auditory sustained attention were associated with reductions in frontal P3 amplitudes before the lapses has occurred, as has been consistently shown with visual sustained attention.

The present study provides the first evidence to show both lapses of auditory and visual sustained attention are associated with reduced frontal P3 amplitudes before the lapse occurs. Also, our findings show that exogenous (stimulus-driven) attentional processes do not support auditory sustained attention during the CTET, as has been observed during the visual CTET. These findings provide support to the interpretations that the frontal P3 is an endogenous (higher order) attentional mechanism, and lapses of sustained attention during a CTET paradigm only affects endogenous (higher order) attentional processing. The theoretical considerations of the current findings are discussed in regard to previous cognitive theories of the frontal P3. Future research should further examine the electrical activity that could predict lapses of auditory sustained attention using the CTET, starting with alpha oscillations.

Abstract

Lapses of sustained attention can have serious consequences in our daily lives. As such, an increasing number of research studies have examined the neural substrates that may predict lapses of sustained attention using the continuous temporal expectancy task (CTET). Previous research has consistently shown reductions in frontal P3 amplitudes are associated with lapses of visual sustained attention, which represents the brief disengagement of endogenous attentional processing prior to a lapse. The present study aimed to extend the current literature by examining the shared and distinct electrophysiological substrates associated with lapses of auditory and visual sustained attention. The present study provides the first evidence that lapses of auditory sustained attention can be predicted by reduced frontal P3 amplitudes up to 4 seconds prior to a lapse. These findings show that both lapses of auditory and visual sustained attention are foreshadowed by similar altered neural activity prior to a lapse. This study also provides evidence that exogenous attentional processing does not support auditory sustained attention throughout the CTET. This provides further support that lapses of sustained attention during the CTET primarily impact endogenous attentional processing, and the frontal P3 is an endogenous attentional mechanism that can track the temporal structure of the task. Theoretical considerations regarding the frontal P3 is discussed, specifically how present findings dispute Polich's (2007) theoretical accounts of the frontal P3 during attentional processing. Future research should consider aim to further examine the neural substrates that may predict lapses of auditory sustained attention, such as alpha oscillatory activity.

Introduction

The ability to sustain your attention or remain alert is becoming increasingly necessary in everyday life, ranging from driving a car and remaining alert to when the car in front brakes, to work environments that require human operators to continuously attend and monitor automated systems for long periods of time. However, attention is a dynamic cognitive process and the ability to sustain one's attention fluctuates over time. In certain context lapses of sustained attention can have serious consequences, such as drops in attention leading to road accidents. Furthermore, impaired sustained attention has been found to be central to a number of psychiatric disorders, such as attention-deficit hyperactivity-disorder (ADHD), schizophrenia, and stroke patients (Brosnan et al., 2021; Chidharom et al., 2021). As such, improving our understanding of sustained attention could help improve current health and safety protocols in workplaces and improve our understanding of treatment and clinical outcomes for individuals who experience attentional deficits. This study aims to examine the shared and distinct neural substrates that are associated with lapses of auditory and visual sustained attention.

There are two main time periods in which attentional processes can be examined, the time period after a target is presented to a participant, known as the downstream effects of attention, and the time period before a target is presented to a participant, known as the upstream effects of attention. Although previous research examining sustained attention has often focused on the downstream consequences of attentional failures during transient target processing while performing highly routine scenarios, over the last decade research has begun to focus on the neural and behavioural factors that may predict lapses of sustained attention (Chidharom et al., 2021; Clayton et al., 2015; Dockree et al., 2017; O'Connell et al., 2009). Research has employed the continuous temporal expectancy task (CTET) to capture lapses of sustained attention, a paradigm in which stimuli only differ in terms of duration and are perceptually identical. As such, this removes any potential for exogenous attentional processing to support sustained attention during the CTET, and that lapses of sustained attention primarily impact higher-order endogenous attentional processes. This has been supported with findings that the P1 and steady-state visual evoked potential (SSVEP), both well-supported indices of bottom-up visual processing, are not affected by lapses of sustained attention during the CTET (Chidharom et al., 2021; Dockree et al., 2017; Koevoet & Kenemans, 2021; O'Connell et al., 2009). However, research has consistently shown that lapses of sustained attention during the visual CTET affect the P300 and alpha oscillatory activity, neural mechanisms that have been consistently observed in cognitive control processes such as inhibition. This study aims to extend the current literature by examining the neural substrates associated with lapses of auditory sustained attention. To the knowledge of the author, there is currently no study that has examined the electrophysiological predictors of sustained attention using an auditory version of the CTET.

Before we discuss the ERP components of interest, a couple of things to note for the reader regarding the terminology for the CTET. The following terminology will be used throughout the paper: the target interval refers to the longer duration after the 800ms timepoint (i.e., each standard trial has a duration of 800ms. During a target trial, the trial will be extended for a longer duration, this additional duration is the target interval. As such, target interval onset is at 800ms, and has a duration of 320ms for visual targets and 170ms for auditory targets; see methods section for more). The pre-target frames refers to the standard frames/tones that occur before the onset of the target interval. Thus, the standard frame/tone that occurs directly before target interval onset is referred to as the pre-target frame. The standard frame/tone that occurs before the pre-target frame is referred to as pre-target – 1, this labelling continues up to pre-target – 4, which would be the fifth standard frame/tone before the target interval onset.

Also, there are two separate periods of cognitive processing that are distinguished as follows; immediate target processing refers to the post target interval onset period, while short-term pre-target processing refers to the 5 standard frames preceding target interval onset. The subsequent sections will discuss the ERP components of interest.

Immediate target processing period

Frontal and parietal P3

Pervious research that has examined auditory attentional processes has often employed the auditory oddball paradigm, a task that requires participants to detect a target tone (e.g., 1000 Hz) from a series of standard tones (e.g., 500 Hz), with the occasional distractor/rare tone occurring (e.g., 1500 Hz). ERP analysis of the downstream effects of attention-demanding stimuli during oddball experiments has shown that target tones elicit a parietal P3 component with a peak amplitude over parietal electrodes, while the distractor tones elicit a frontal P3 component with a peak amplitude over frontal electrodes (Katayama & Polich, 1996). According to Polich (2007), the frontal and parietal P3 may reflect general neural inhibition of on-going activity to facilitate the transmission of stimulus/task relevant information from the frontal to temporal-parietal regions. Polich's cognitive model suggests that the occurrence of the frontal P3 during task processing reflects stimulus-driven frontal attention mechanisms, while the parietal P3 reflects memory updating operations. Specifically, when attention-demanding stimuli differ from the contents of working memory, a frontal P3 is produced. The frontal P3 is said to reflect neural inhibition of extraneous neural activity that facilitates the initiation of neural activity in the parietal areas associated with memory processes (Wessel & Aron, 2013), leading to the production of the parietal P3. This general inhibition hypothesis may be supported by sustained attention research findings.

Regarding the downstream effects of lapses of visual sustained attention (after target presentation), research findings have shown that the parietal P3 was significantly larger for hits compared to misses, and the frontal P3 during hits occurred significantly earlier compared to misses (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009; Pinggal et al., 2022). Furthermore, studies also showed the presence of the frontal P3 occurred in the absence of any stimulus change, which the authors suggest indicates that the frontal P3 is a top-down endogenous mechanism that actively tracks the temporal structure of the CTET. These findings do not align with Polich's (2007) cognitive model, which states that the frontal P3 is produced when attention demanding stimuli differ from the contents of working memory. However, these findings may support the argument that unexpected events automatically elicit a frontal P3 that serves a similar generic inhibition function as the stop P3 (Kenemans, 2015; Wessel & Aron, 2013). Thus, the differences in frontal P3 activity between hits and misses during the target-interval appears to be related to stimulus-driven frontal endogenous attention mechanisms. In the context of the visual CTET, the frontal P3 actively track the temporal structure of the task to inhibit extraneous neural activity to facilitate the detection of a target.

To further support the potential endogenous nature of the frontal and parietal P3 observed during sustained attention, Justen and Herbert (2018) employed passive and active auditory oddball paradigms. Their findings show frontal and parietal P3 activity during successful target detection is associated with activation throughout the dorsal attention networks (DAN). Crucially, the study's ERP and LORETA results indicate that DAN activation only occurs during active listening conditions and later stages of target detection, and frontal and parietal P3 amplitudes were significantly larger for targets during the active listening compared to passive listening conditions. The authors suggest that active listening processing is taken over and driven by attention networks, with voluntary, top-down controlled brain regions supporting the later stages of successful target detection (i.e., the frontal and parietal P3).

Thus, given 1) the proposed endogenous nature and temporal role of the frontal P3 that is observed during the target interval of the visual CTET; and 2) auditory oddball findings show frontal and parietal P3 modulation of target detection during active listening processing is governed by top-down attentional networks; this paper hypothesizes that the downstream effects (after target presentation) of lapses of auditory sustained attention during the auditory CTET will also be reflected in altered frontal P3 and parietal P3 activity.

N100

Another ERP component of interest that may be associated with auditory sustained attention is the N1, a frontocentral negative ERP component that occurs approximately 100ms post stimulus onset and is said to reflect detection and discrimination of auditory stimuli (Campbell et al., 2007; Tomé et al., 2015). As stated above, previous research that has examined auditory attentional processes has often employed auditory oddball paradigms. Recent research findings (Justen & Herbert, 2018) have shown N1 amplitudes are significantly increased to target tones compared to standard tones during passive and active oddball paradigms. Regarding the passive auditory oddball findings, they are in line with previous explanations that neurons within the auditory cortex are susceptible to refractoriness and display selective sensitivity to different frequencies. As such, repeated presentation of standard tones (500 Hz) leads to habituation of neurons that react to the standard tone, leading to reduced electrical activity. Whereas the target tone occurs less frequently than the standard tone, neurons within the auditory cortex that respond to the target tone (1000 Hz) show much greater electrical activity. These findings are supported with LORETA results displaying activation within the auditory cortex and multisensory association areas during passive listening conditions. Thus, during passive listening conditions, the early stages of deviance processing are supported by neural activation of sensory brain regions associated with attention.

However, more importantly within the scope of this study, LORETA results showed that during active listening conditions, the early processing stages of auditory deviance processing (0-200ms; i.e., the N1 and MMN) elicits inferior parietal lobule (IPL) activation, a brain region that is part of the ventral attention network (VAN). The VAN is a frontoparietal attentional network that supports the detection of behaviourally relevant and salient stimuli (Kim, 2014; Vossel et al., 2014). As such, during active listening conditions, the early stages of deviance processing may be fully taken over by the VAN, and do not rely on sensory processing to support target discrimination. Justen and Herbert (2018) suggest their findings indicate that VAN activation during the early stages of auditory deviance processing may be caused by anticipatory control of attention in order to support voluntary selection of target stimuli. Thus, during active listening conditions, N1 modulation of target discrimination may represent a stimulus-driven mechanism that reflects exogenous attentional processing.

Thus, this study hypothesises that lapses of auditory sustained attention will be reflected in altered N1 activity during the post-target processing period. Specifically, this study expects that successfully detected target tones during the auditory CTET will display larger N1 amplitudes compared to missed target tones. This hypothesis is based on 1) previous electrophysiological (ERP and LORETA) and neuroimaging (PET and fMRI) research findings that have shown early stages of detecting behaviourally relevant auditory stimuli is supported by the VAN; and 2) the design of the CTET, in that each tonal frequency has an equal probability of being presented as a standard or target tone, and the distinction between standard and target tones should not rely on stimulus-driven perceptual processes. As such, this removes the design limitation observed in auditory oddball experiments, in that, any potential differences observed in auditory ERP amplitudes between hits and misses should not be reflected by habituation effects within the auditory cortex neurons.

The next section will discuss the electrophysiological activity during the preceding non-target frames (i.e., pre-target period).

Short term pre-target processing period

As stated previously, auditory novelty processing experiments have often employed the auditory oddball paradigm when examining auditory attentional processes. According to the context updating theory of the P300 (Polich, 2007), when a presented stimuli enters the processing system a working memory comparison process is engaged to determine whether the presented stimuli is the same or different than the previous stimuli. When the stimuli are the same, only sensory evoked potentials are observed (N1, P2, N2). Whereas, when the presented stimuli differ from the contents of working memory (i.e., a distractor stimulus is presented), attentional processes are allocated to the presented target stimulus, which elicits a frontal P3. This would suggest that no frontal or parietal P3 would be visible after each non-target frame during the CTET. However, as seen in previous research that has employed the visual CTET, non-target frames elicit a frontal P3 (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009; Pinggal et al., 2022). Furthermore, Martel et al., (2014) used a modified version of the Mackworth Clock Task (Mackworth, 1948; a covert vigilant task that assesses endogenous attentional mechanisms in a similar fashion as the CTET) to examine the electrophysiological activity associated with lapses of sustained attention, and also found a reduction in central P3 amplitude during the non-target frames preceding a target. The presence of a frontal P3 during non-target frames of the CTET can be explained by the allocation of endogenous attentional resources.

During an auditory oddball paradigm, due to the difference in tonal frequencies between target and non-target stimuli, each stimulus can be differentiated at the beginning of each trial. In other words, attentional processes are engaged at the start of each stimulus, but are not sustained throughout each stimulus. As such, due to distinct tonal frequencies, successful target detection during an auditory oddball paradigm is sufficiently supported by exogenous attentional processes (Justen & Herbert, 2018). Therefore, when a non-target stimulus is presented, exogenous attentional processes can determine that the presented stimuli does not differ from previous stimuli and indicate that endogenous attentional processes are not required. This would be in line with the dynamic interaction between the exogenous and endogenous attention networks (Vossel et al., 2014). Thus, no frontal or parietal P3 is observed during non-target trials of an oddball paradigm. However, due to the design of the CTET, target and non-target stimuli can only be differentiated at the end of each trial, as that is when the onset of the target interval occurs. As a result, successful target detection during the CTET relies on sustained attentional processing, and endogenous attentional processes continue to operate throughout the duration of each trial. Thus, top-down attentional processes will operate throughout every trial to support the ability to detect the target interval, and as such, a frontal P3 component will be elicited across every trial (O'Connell et al., 2009). Therefore, although Polich's (2007) context updating theory of the P300 would suggest that only early sensory potentials would be observed after each non-target stimuli, within the context of the CTET, this study expects to observe a frontal P3 after each non-target frame.

In addition, research has shown the characteristics of the frontal P3 can change across modalities. Previous literature that has examined the modality effects of the frontal and parietal P3 have stated that the general consensus within the literature is auditory-evoked frontal and parietal P3 amplitudes are smaller and latencies are earlier compared to visually-evoked frontal and parietal P3 components, but the topographical distribution remains the same across modality (Tekok-Kilic et al., 2001). These differences are said to be caused by differences in transmission time to the cortex (Picton et al., 1984), and have been shown across single stimulus, 2- and 3-stimuli oddball paradigms (Pfefferbaum et al., 1984; Polich &

Heine, 1996; Romero & Polich, 1996) and Go/NoGo paradigms (Falkenstein et al., 2002; Tekok-Kilic et al., 2001). Furthermore, modality effects of the frontal P3 have also been observed during the stop-signal task, in which the stop P3 displayed shorter latencies to auditory stop signals compared to visual stop signals (Kenemans et al., 2022; Ramautar et al., 2006). Thus, this study expects that auditory-evoked frontal and parietal P3 components will occur earlier than visually evoked frontal and parietal P3 components, while the topographical characteristics will remain the same across modalities.

It should also be noted that this study does not expect the N1 to play a significant modulatory role for successful target detection during the preceding non-target frames. As previously discussed regarding the post-target period of attentional processing, during active listening conditions of auditory oddball paradigms, N1 modulation of target detection was generated in the VAN (IPL), a frontoparietal attentional network that supports the detection of behaviourally relevant and salient stimuli (Kim, 2014; Vossel et al., 2014). Researchers have suggested that this indicates the N1 may reflect anticipatory control of attention during active listening (Justen & Herbert, 2018). Although this may provide some premise to the N1 contributing to lapses of sustained attention during pre-target processing, it is unlikely to be the case during the CTET due to target and non-target stimuli only differing in terms of duration and are perceptually identical. As previous research has shown with the visual CTET, bottom-up visual processing does not contribute to lapses of visual sustained attention, and the effects associated with lapses of visual sustained attention during the pre-target frames of the CTET are governed by endogenous attentional processes.

Thus, given that previous LORETA findings of auditory evoked potentials have shown top-down attentional networks (DAN) only support target detection during later time windows (frontal and parietal P3), and previous findings that lapses of sustained attention during the CTET are only affected by endogenous attentional mechanisms; it is not expected that exogenous attentional mechanisms such as the N1 will have display predictive properties of lapses of auditory sustained attention.

Conclusion

To conclude, research has shown that lapses of visual sustained attention are predicted by altered frontal P3 activity during the preceding non-target frames (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). However, no research to date has examined the electrophysiological substrates associated with lapses of auditory sustained attention. Thus, the present study aims to examine the electrophysiological processes that can predict transient lapses of both visual and auditory sustained attention using the CTET. This study aims to compare the neural mechanisms underlying the distinct modalities (visual and auditory) of sustained attention to improve our understanding of the modality differences observed in previous behavioural research.

Hypotheses

The following hypotheses will be tested within this study: First, this study aims to replicate previous research findings regarding lapses of visual sustained attention (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). Specifically, this study expects to show that lapses of visual sustained attention will be predicted by altered frontal P3 activity during the preceding non-target frames. Specifically, unsuccessful target detection (i.e., lapses of sustained attention) will be associated with reduced frontal P3 amplitudes over frontocentral electrodes up to 4 seconds prior to a miss. Furthermore, this study aims to replicate previous research findings regarding the downstream effects of target detection during the CTET. Specifically, this study hypothesises that successful target detection will lead to an increase in parietal P3 amplitudes and earlier onset of frontal P3 latencies relative to unsuccessful target detection.

Regarding the auditory CTET, the following hypotheses will be tested: First, this study expects to show similar downstream effects of target detection during the auditory CTET as has been observed during the visual CTET. Specifically, this study hypothesises that successful auditory target detection will lead to an increase in N100, frontal and parietal P3 amplitudes relative to unsuccessful auditory target detection. Furthermore, regarding the activity during the preceding non-target frames, this study hypothesises that lapses of auditory sustained attention will be associated with reductions in frontal P3 amplitudes, like findings observed during the visual CTET (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). Furthermore, this study hypothesises that auditory-evoked frontal P3 components will occur earlier than visual-evoked frontal P3 components. This study also hypothesises that N100 activity during the preceding non-target frames will not modulate lapses of auditory sustained attention. This will provide further premise that lapses of sustained attention primarily impact higher-order endogenous attentional processing, and the temporal structure of the CTET is tracked by an endogenous attentional mechanism.

Methods

Participants

29 individuals participated in this study (female *N* = 14, age *M* = 24.43, *SD* = 3.71). All participants were free of psychiatric and neurological disorders, were non-smokers (no nicotine), had normal or corrected-to-normal vision, and had no prior exposure to the stimuli. Also, due to the known effects that substances have on sustained attention (Böcker et al., 2010; Dockree et al., 2017; Gilbert et al., 2000) participants were asked to abstain from ingesting coffee, alcohol, stimulants, or other drugs after 10pm from the night before their participation. All participants provided written informed consent before participation, and this research was approved by Utrecht University's ethical review board of the Utrecht University faculty of social sciences.

Continuous Temporal Expectancy Task (CTET)

The present study employed a visual and auditory version of the CTET. The visual CTET was first introduced by O’Connell et al., (2009). The auditory CTET was first introduced by Berry et al., (2014). During the visual CTET, participants are exposed to a continuous stream of ‘frames’. Each frame consisted of a centred pattern stimulus, a 10x10 checkerboard casting a visual angle of 8° 1' 0.70". Each square of the checkerboard was split diagonally into black and white halves, and the background was grey. Each frame-change rotated the grid 90° in a random direction, providing 4 different grids (see figure 1). Participants were instructed to look at the white fixation cross in the centre of the grid to limit eye movements. The visual stimulus flickered at a constant rate of 10Hz, which was used to evoke the steady-state visual evoked potential (SSVEP; O’Connell et al., 2009) to provide an index of basic visual processing (Müller & Hillyard, 2000; O’Connell et al., 2009).

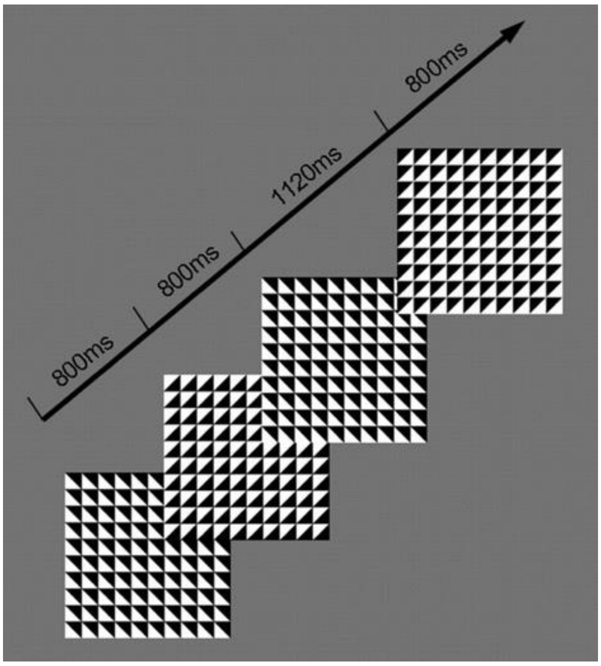

Figure 1. *Overview of the visual CTET*. Note. Non-target frames were presented for 800ms. Target frames were presented for 1120ms. Stimuli flickered at a constant rate of 10Hz. From O’Connell et al. (2009).

Throughout the auditory CTET, participants were exposed to a continuous stream of sine wave tones played through earbuds (ER3C Insert Earphones, Etymotic Research) at a sound pressure of 50dB to 65dB (participants could ask to adjust the volume of the auditory stimuli, the minimum dB level allowed was 50dB, and a maximum dB level of 65dB) while viewing a white fixation cross on a screen with a grey background to limit eye movements (see figure 2). Unlike the visual CTET, there was no flicker of the monitor screen. Previous use of the auditory CTET (Berry et al., 2014) used a 500Hz square tone for the auditory stimulus, with each trial separated by a 20ms empty interval. The only parameter that differed between the standard and target tones was the duration.

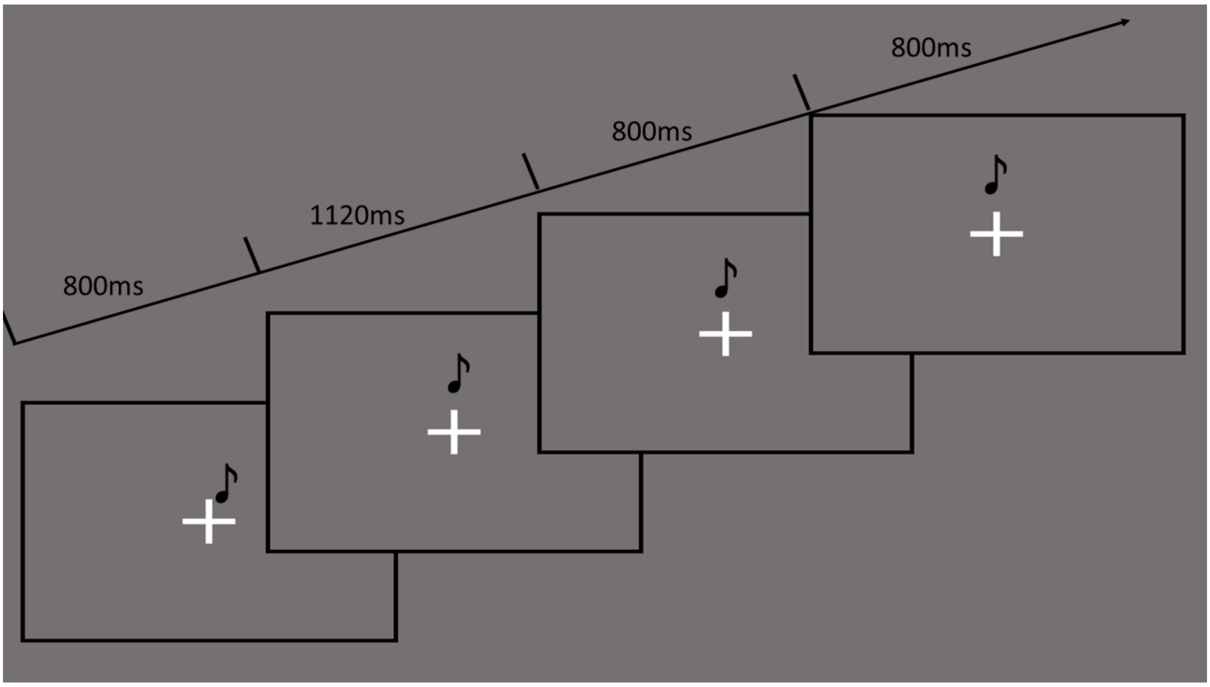

Figure 2. *Overview of the auditory CTET*. Note. Non-target frames were presented for 800ms. Target frames were presented for 1120ms. There were 4 different tones with different pitches, a 500Hz, 625Hz, 750Hz, and 875Hz tone.

However, in order to eliminate potential modulatory or habituation effects of tonal frequency on electrophysiological activity during the auditory CTET (Antinoro & Skinner, 1968; Pantev et al., 1995; Picton et al., 1978; Polich et al., 1985; Teichert, 2016; Verkindt et al., 1995; Wood et al., 1983), the present study used tonal frequencies below 1000 Hz for the auditory stimuli with linear steps of frequency increases (500, 625, 750, 875 Hz). Tones below 1000 Hz were chosen as EEG research has not indicated any statistical differences in ERP amplitude or latency between low tonal frequencies (< 1000 Hz) but has observed differences in ERP amplitude and latency between low and high tonal frequencies (< 1000 Hz vs > 2000 Hz; Picton et al., 1978; Polich et al., 1985; Teichert, 2016). Furthermore, as the frequencies noticeably differ on a trial-to-trial basis, there was no empty (silent) interval between each trial as stimuli were presented successively.

Participants were instructed to identify target tones/image, which had an increased duration compared to non-target tones/images. To remain consistent with previous literature that has employed the visual CTET, the duration for target images was set to 1120ms and for standard images set to 800ms. In order to compare the electrophysiological predictors of visual and auditory sustained attention under the same conditions, this study aimed to equate the task performance of the visual and auditory CTET (de Jong et al., 2009). Two pilot sessions were carried out in which the target durations were titrated until the performance levels of the auditory CTET and visual CTET were matched. Results from these titration sessions suggested performance would be matched with a duration of 970ms for target tones (i.e., 150ms less than the duration of the target images in the visual CTET).

Participants were instructed to press the spacebar with their dominant index finger when they identified a target. In line with previous literature (Dockree et al., 2017), button presses recorded within two nontarget frame (1600ms) after termination of the target stimuli were coded as target detections (hits). Stimuli were presented in pseudo-randomised order, which provided 7-15 nontarget tones (average of 11 tones/images) or 5.6 to 12 seconds (average of 8.8 seconds) between each target tone/image. There were 10 blocks with small breaks (approximately 1min) between each block. Each block contained 255 tones and took approximately 3 minutes and 25 seconds. The number of target tones/images varied between 199-213 across the task, with an average of 206 target tones/images.

Before starting the task, each participant completed two practice blocks. In order to establish that participants understood the task, target tone/image presentation was set to 1280ms during the practice blocks. In both practice block participants were required to detect three target tones/images in random order amongst 25 nontarget tones/images. For the visual CTET, the 10Hz flicker was omitted in the first practice block but was included in the second practice block. Each participant had to display 100% accuracy during the practice blocks to confirm that the comparison between the target and standard tone/image was well above individual detection thresholds (O'Connell et al., 2009). Furthermore, participants who displayed a hit to false alarm (H/FA) rate of below 3 were excluded from analysis, thus removing participants who were not able to perceptually distinguish between target and non-target trials.

Of the 29 participants that completed the visual CTET, 14 participants were excluded from analysis due to inadequate H/FA rates, thus providing a final sample of 15 participants. Analysis showed 56% of targets were successfully detected (SD = .22) with an average RT of 744ms (SD = 104ms). The rate of false alarms (M = 11.24, SD = 7.68) were increased compared to previous research (O'Connell et al., 2009). However, given the strict exclusion criteria for adequate performance (i.e., H/FA > 3), we were confident participants could perceptually distinguish target trials from non-target trials.

Of the 29 participants that completed the auditory CTET, 16 participants were excluded from analysis due to inadequate H/FA rates, thus providing a final sample of 13 participants. Analysis showed 76% of targets were successfully detected (SD = .16) with an average RT of 651ms (SD = 69ms). Only 5.1% of responses were classified as false alarms, indicating that participants were successfully able to perceptually distinguish between target and non-target trials.

EEG recording

The EEG signal was recorded using a 64-channel BioSemi ActiveTwo EEG system, with the Driving Right Leg and Common Mode Sensor as ground and reference electrodes. The following electrode positions were used; Fpz, AFz, Fz, FCz, Cz, CPz, Pz, POz, Oz, FP1/2, AF3/4/7/8, F1/2/3/4/5/6/7/8, FC1/2/3/4/5/6; FT7/8; C1/2/3/4/5/6; T7/8; CP1/2/3/4/5/6; TP7/8; P1/2/3/4/5/6/7/8; PO3/45/6/7/8; O1/2. Facial electrodes were used to record electrical activity produced by eye blinks and movements, they were placed ~1cm above and below the left eye to record vertical electrooculogram (EOG); and two electrodes placed ~1cm beyond the outer edge of each eye to measure horizontal EOG. Data was recorded at a sampling rate of 2048Hz with online low pass filtering at 417Hz while referencing to the Common Mode Sense/Driven Right Leg electrodes using the ActiView Software. Two electrodes were placed on the mastoids for offline re-referencing during EEG pre-processing. An electrode was also placed on the nose for offline re-referencing for additional analysis.

EEG pre-processing

Brain Vision Analyser software Version 2.1 (Brain Products, Munich, Germany) was used to analyse the EEG data. Data were down-sampled to 256 Hz, referenced to the average mastoid electrodes, and filtered using a 0.1 Hz high-pass filter, a 40 Hz low pass filter, and a notch filter at 50 Hz to attenuate power-line noise. The signal was segmented into epochs of 6200ms, 3200ms before target frame onset to 3000ms post onset to allow for a broader time frame to perform artifact rejection[1]. A 10 Hz notch filter was applied to remove activity from the SSVEP (only applied for visual ERP analysis). Eye blinks were removed using ICA ocular

[1] Trials were rejected when a voltage step exceeded the 50 µV/ms, amplitudes exceeded ± 200 µV or when the lowest activity within an interval of 100ms was lower than 0.5 µV.

correction. Also, to ensure that missed targets were not caused by eye blinks, trials were rejected in which VEOG activity exceeded ±200 µV of change within a time period of -1000ms to 200ms relative to target interval onset. Like previous research (Dockree et al., 2017; O'Connell et al., 2009), the number of hit and miss trials were unequal and the inter-target intervals (ITIs) significantly differed between hits and misses. To ensure ITI length would not confound EEG results (Polich, 1990), trials from the overrepresented condition (hits or misses) were pseudo-randomly selected for each ITI, resulting in the equal representation of ITI in both conditions. The following sections will discuss the ERP analysis performed during the two processing periods; immediate target processing refers to the post target onset period, while short-term pre-target processing refers to the 5 standard frames preceding target interval onset.

Also, regarding the choice of electrodes for the ERP analysis, there will be two forms of analyses complete for each ERP component. A cluster approach (analysing a group of electrodes) will be conducted to account for the variance of each ERP component across several electrode sites. A single-electrode analysis of each ERP component will also be conducted to improve the sensitivity of the analysis at the electrode site in which each component peaks. The same latency windows were used for both approaches. It is expected that both approaches will provide similar statistical findings.

Immediate target processing

Visual ERP analysis

The data was then segmented into epochs from -100ms to 1800ms relative to pre-target frame onset and separated between hits and misses. Remaining consistent with previous research (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009), the baseline period was defined as 560ms to 640ms post pre-target frame onset for ERP analysis. Using a collapsed localiser, visual inspection of grand average waveforms and associated topographical maps were complete to identify each ERP component. The width of the latency window used to measure each ERP component was aided by previous research (Dockree et al., 2017; O'Connell et al., 2009) and based on the duration and spatial extent of each ERP component. This procedure resulted in the identification of the following ERP components: a late positive wave over frontocentral electrode sites (Fz; ~1200ms; frontal P3); and finally, a late positive wave over central parietal electrode sites (Pz; ~1450ms; parietal P3). Thus, for the cluster analysis, the CNV was measured from a group of electrodes surrounding the CPz (CPz/1/2/3/4) electrode throughout the interval 900-1100ms, the late positive wave was measured around its dominant peak during the interval 1300-1600ms at frontal (Fz/1/2, FCz, AFz) and parietal (Pz/1/2, CPz, POz) electrode sites. Also, the frontal P3 was measured throughout the interval 1100-1300ms and assessed at frontocentral electrodes to further analyse the differences of the frontal P3 between hits and misses. For the single-electrode analysis, each ERP component was assessed at the electrode site that the component peaks. The CNV was measured from the CPz electrode, the late positive wave was measured from the Fz and Pz electrodes, and the frontal P3 was measured from the Fz electrode.

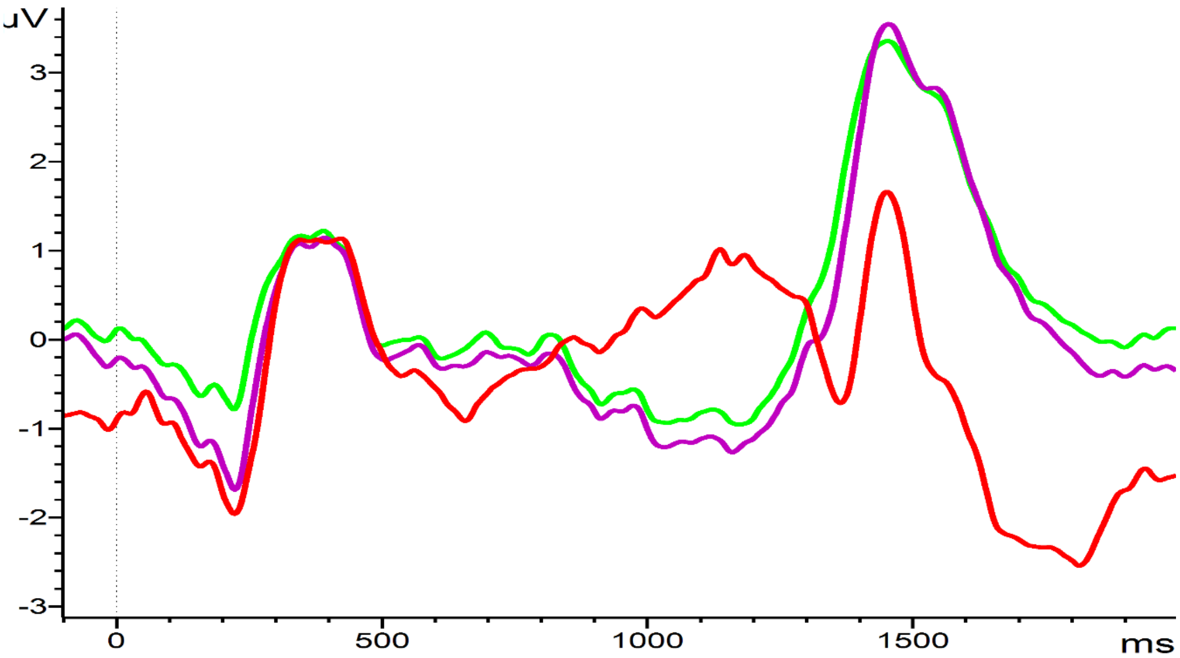

Figure 3. *Grand averaged ERP waveform of the pre-target frame and target interval collapsed across hits and misses for the visual CTET.* Note. Colour coding goes as follows: Green, Pz electrode; Red, Fz electrode; Purple, CPz electrode. Target interval onset occurs at 800ms and ends at 1120ms. Baseline correction is set at 560ms to 640ms post pre-target frame onset.

Auditory ERP analysis

The data was segmented into epochs from -100ms to 1800ms relative to pre-target frame onset and separated between hits and misses. The baseline period was defined as 600ms to 700ms post pre-target frame onset for ERP analysis. Using a collapsed localiser, visual inspection of grand average waveforms and associated topographical maps were complete to identify a suitable baseline period and each ERP component.

This procedure resulted in the identification of the following ERP components: a N1 over the left and right parietal region, maximal at 950ms; a late positive wave over the frontocentral electrode sites (FCz; ~1150ms; frontal P3); a late positive wave over parietal electrode sites (Pz; ~1300ms; parietal P3). Thus, for the cluster analysis, the N1 was measured from the a group of left and right parietal electrodes (left, CP1/3/5; right, CP2/4/6) throughout the interval 900-1000ms post pre-target frame onset, the late positive wave was measured around its dominant peak during the 1100-1300ms interval at a group of frontocentral (FCz/1/2) and parietal (Pz/1/2) regions. For the single-electrode analysis, the N1 was measured from the CP3/4 electrodes, and the late positive wave was measured from the FCz and Pz electrodes.

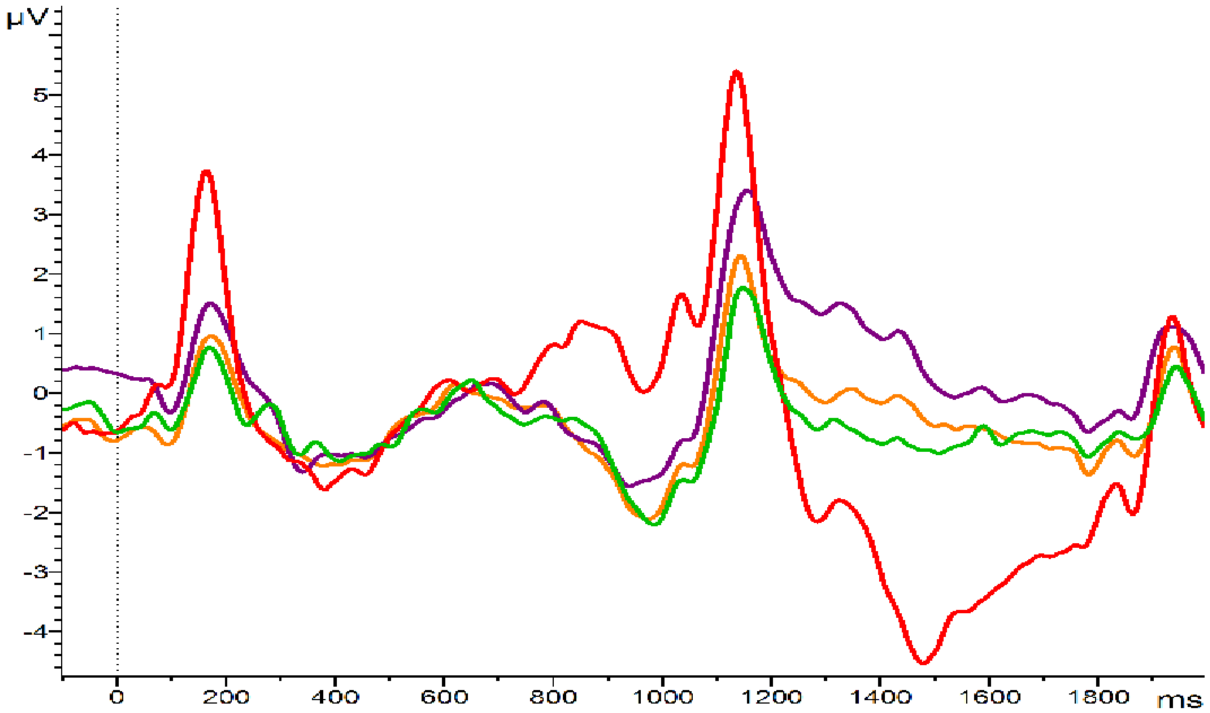

Figure 4. *Grand averaged ERP waveform of the pre-target frame and target interval (800-1120ms) and interval collapsed across hits and misses for the auditory CTET.* Note. Colour coding goes as follows: Red, FCz electrode; Orange, CP3 electrode; Green, CP4 electrode; Purple, Pz electrode. The target interval onset occurs at 800ms and ends at 970ms. Baseline is set at 600ms to 700ms post pre-target frame onset.

Short-term pre-target processing

Next, our analysis involved examining the event related potentials (ERP) and oscillatory activity within a 4 second time-period before target interval onset, which encompassed five pre-target frames. A 4 second window was chosen to allow for the analysis of pre-target electrophysiological activity while ensuring results would not be confounded by activity of the previous target frame. This is because the minimum interval between targets is 7 standard frames (5.6 seconds).

Visual ERP analysis

For analysing the ERP components, data was segmented into epochs of -3280ms to 800ms relative to target interval onset. A 10 Hz notch filter was applied to remove activity from the

SSVEP (only applied for visual ERP analysis). Each of the five pre-target frames were baseline corrected -80ms to 0ms relative to the onset of each separate frame. ERP components of interest were chosen using guidelines from previous research (O'Connell et al., 2009) and visual inspection of grand averaged waveforms. This procedure resulted in the identification of the following ERP components within the standard frames: a negative wave (N170) over the central occipital electrode (Oz) peaking at 170ms, and a positive wave (frontal P3) over the frontal electrode sites (AFz, FCz, Fz/1/2) peaking at 350ms. Thus, for the cluster analysis, the frontal P3 was measured from a group of frontocentral electrodes throughout the 280-400ms post frame onset. The N170 was not analysed through the cluster analysis approach as the component was only present at the Oz electrode. For the single electrode analysis, the N170 was measured from the Oz electrode throughout the 140-220ms post frame onset, and the frontal P3 was measured from the Fz electrode.

Similar to previous CTET analyses, to reduce the likelihood that differences between hits and misses may be confounded by activity differences within the pre-stimulus baseline, ERP component amplitudes were assessed by subtracting the amplitude at component onset from the peak amplitude. For the N170, component onset was set at 20ms to 100ms post frame onset; while for the frontal P3, component onset was set at 80ms to 160ms post frame onset.

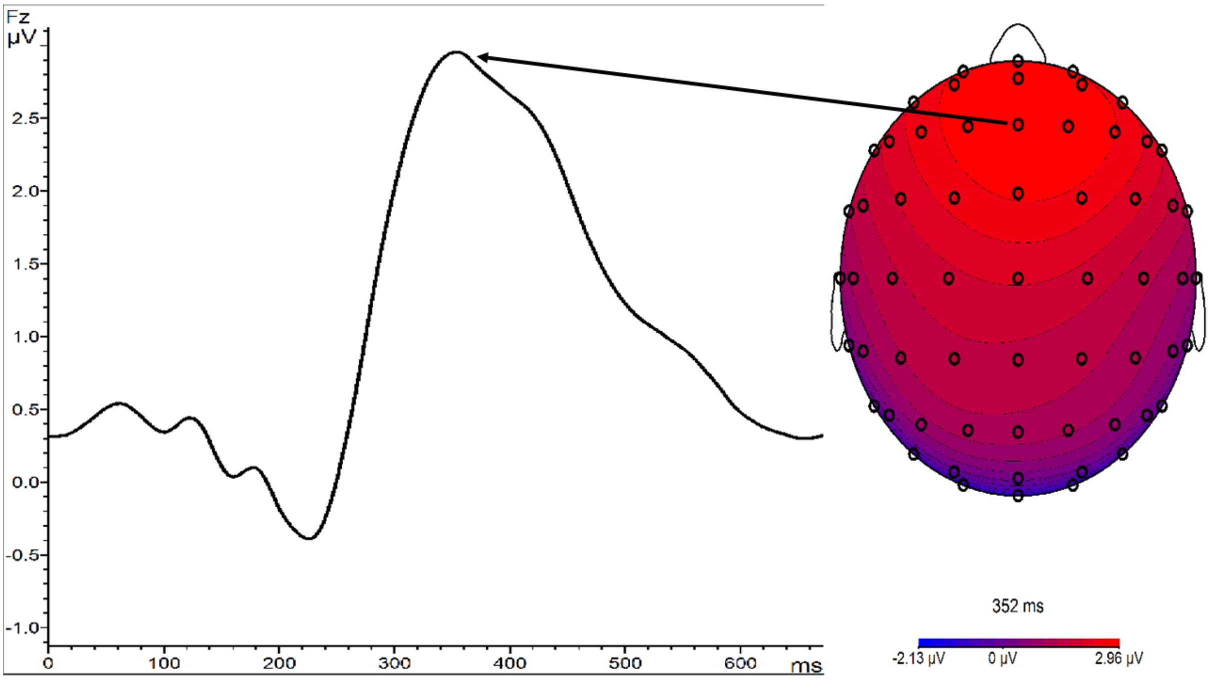

Figure 5. *Grand averaged ERP waveform of the five pre-target frames before the target interval and collapsed across hits and misses for the visual CTET.* Note. The ERP waveform represents the Fz electrode, where the frontal P3 reaches maximum amplitude. Baseline is set at 80ms to 160ms post frame onset.

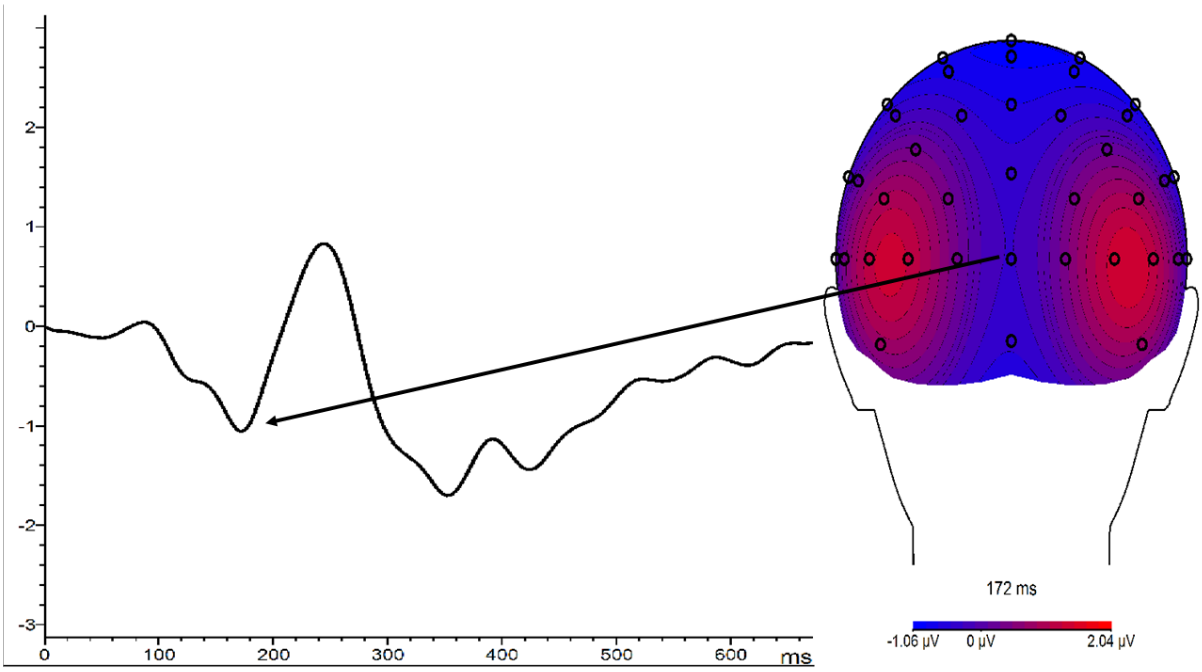

Figure 6. *Grand averaged ERP waveform of the five pre-target frames before the target interval and collapsed across hits and misses for the visual CTET.* Note. The ERP waveform

represents the Oz electrode, where the N170 reaches maximum amplitude. Baseline is set at 20ms to 100ms post frame onset.

Auditory ERP analysis

For analysing the ERP components, data was segmented into epochs of -3280ms to 800ms relative to target interval onset. Each of the five pre-target frames were baseline corrected -80ms to 0ms relative to the onset of each separate frame. ERP components of interest were chosen using guidelines from previous research (O'Connell et al., 2009) and visual inspection of grand averaged waveforms. This procedure resulted in the identification of the following ERP components within the standard frames: a N1 over the parietal electrode sites, maximal at the P1 electrode (~100ms); and a frontal P3 over the frontocentral electrode sites, maximal at the FCz electrode (~180ms). Thus, for the cluster analysis, the N1 was measured from a group of parietal electrodes (Pz/1/2/3) throughout the 80-120ms interval post frame onset, and the frontal P3 was measured from a group of frontocentral electrodes (FCz/1/2) throughout the 120-220ms interval post frame onset. For the single-electrode analysis, the N1 was measured from the P1 electrode, and the frontal P3 was measured from the FCz electrode.

Similar to the visual pre-target ERP analysis, ERP components were assessed by subtracting the amplitude at component onset from the peak amplitude. For the N1, component onset was set at -20ms to 60ms post frame onset; while for the frontal P3, component onset was set at 60ms to 120ms post frame onset.

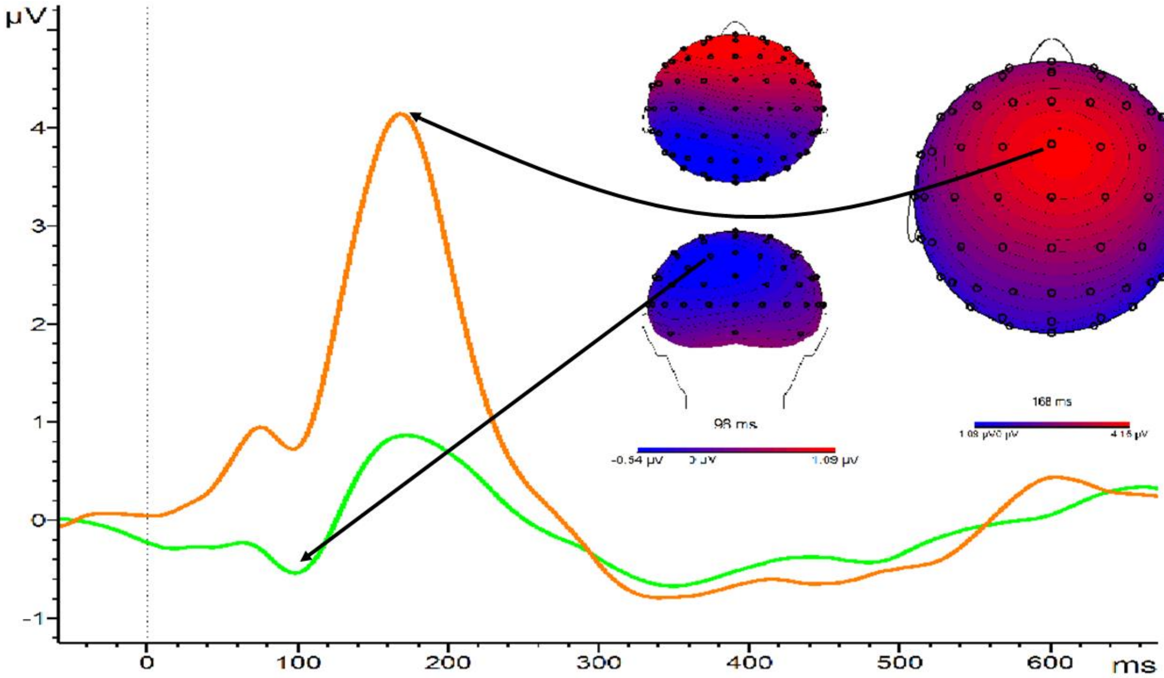

Figure 7. *Grand averaged ERP waveform of the five pre-target frames before the target interval and collapsed across hits and misses for the auditory CTET.* Note. Colour coding goes as follows: Orange, FCz electrode; Green, P1 electrode. Baseline is set at -20ms to 60ms for the N1; 60ms to 120ms for the frontal P3.

Statistical analysis

All statistical analyses were performed on IBM SPSS-software (version 28). Behavioural analysis of hits rates assessed the differences in auditory and visual CTET performance, while also comparing performance to previous research. As such, both auditory and visual hit rates, false alarm rates, average reaction times (RTs) and RT variability were calculated. RTs were measured from the time point that distinguishes targets from non-targets (target interval onset). To remain consistent with previous CTET analysis, hit rates were calculated across each block and across 12- bins, with each time bin consisting of 40 frames with a 50% overlap. RMs ANOVA (within factors: block and time) were used to examine the effects of blocks and time bins.

Regarding the data analysis of EEG data: Using the cluster analysis approach, for the immediate target processing period, RMs ANOVA were performed to examine the differences between hits and misses of the CNV (visual), the N1 (auditory), and the frontal and parietal P3 (visual and auditory). For the short term pre-target processing, RMs ANOVA were performed to examine the differences between hits and misses of the CNV (visual), N1 (auditory), and the frontal and parietal P3 (auditory and visual).

Using the single-electrode analysis approach, for the immediate target processing period, paired sample t-test were performed to examine the differences between hits and misses of the CNV (visual) and the N1 (auditory). RMs ANOVA were performed to examine the differences between hits and misses of the frontal and parietal P3 (visual and auditory). For the short term pre-target processing, RMs ANOVA were performed to examine the differences between hits and misses of the CNV (visual), N1 (auditory), and the frontal and parietal P3 (auditory and visual).

Results

Behavioural task data

As in previous research, in order to ensure that the target/non-target discrimination was well above perceptual threshold and successful hits were not due to chance, participants with a hits/false-alarm (H/FA) rate of below 3 were excluded from the analyses.

Visual CTET

RMs ANOVA (within factor: block, 10 levels) showed that blocks had no effect on performance, $F(3.68, 51.54) = .95$, $p = .44$. Also, RMs ANOVA (within factor: time bin, 12 levels) revealed a significant effect of time bins within blocks, $F(4.14, 58.01) = 7.19$ $p < .001$. Both results are in line with previous research (O’Connell et al., 2009), indicating that task performance declined within each block, task performance did not deteriorate across the whole task.

Auditory CTET

RMs ANOVA (within factor: block, 10 levels) showed that block significantly affected task performance, $F_{(4.21,\ 50.52)} = 2.55$, $p = .011$. Furthermore, RMs ANOVA (within factor: time bins, 12 levels) revealed a significant effect of time bins within blocks, $F_{(5.35,\ 58.83)} = 6.43$, $p < .001$, in which linear polynomial trends were significant ($p < .001$) but not quadratic ($p = .07$). Similar to the visual CTET, results indicate that task performance declined within blocks during the auditory CTET. However, unlike the visual CTET, analysis showed task performance declined across the auditory task. It is important to note, because of software limitations, the auditory CTET was split into 3 parts, with part 2 beginning on the 5^{th} block. This may explain the sharp increase in hit rates in block 5 (see figure 8). When the 5^{th} block is removed from analysis, blocks no longer significantly affect task performance, $F_{(1,96)} = 1.48$, $p = .18$.

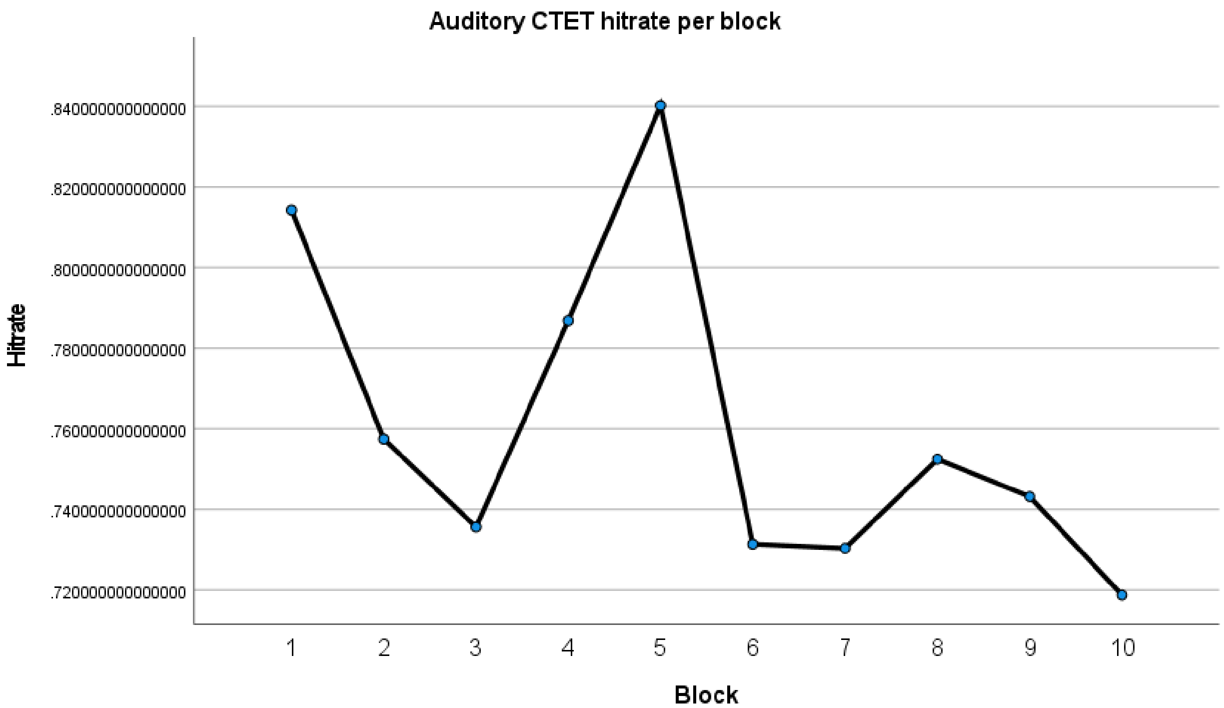

Figure 8. *A line graph displaying the hit rates per block throughout the auditory task*. Note. Part 2 of the auditory task began at the fifth block.

Visual ERP analysis - Immediate target processing

CNV

Previous research has found during target trials, the CNV amplitude continues to grow into the target interval (800-1120ms), but to a significantly greater degree before a hit compared to a miss (O'Connell et al., 2009). These findings provided support to the notion that an increase in CNV activity is consistent with a build-up of anticipatory activity (Macar & Vidal, 2004). However, regarding the cluster analysis, RMs ANOVA (within factors: detection – hit and miss; CNV – CPz/1/2/3/4) findings showed no significant difference in CNV amplitude between hits and misses, $F_{(1,14)}$ = .82, p = .382 (see figure 9).

Furthermore, paired sample t-tests findings showed no significant differences between hits (M = 2.02, SD = 2.14) and misses (M = 1.43, SD = 1.3) at the CPz electrode, t(14) = -.85, p = .411. Thus, both cluster and single-electrode findings do not support previous research findings (O'Connell et al., 2009).

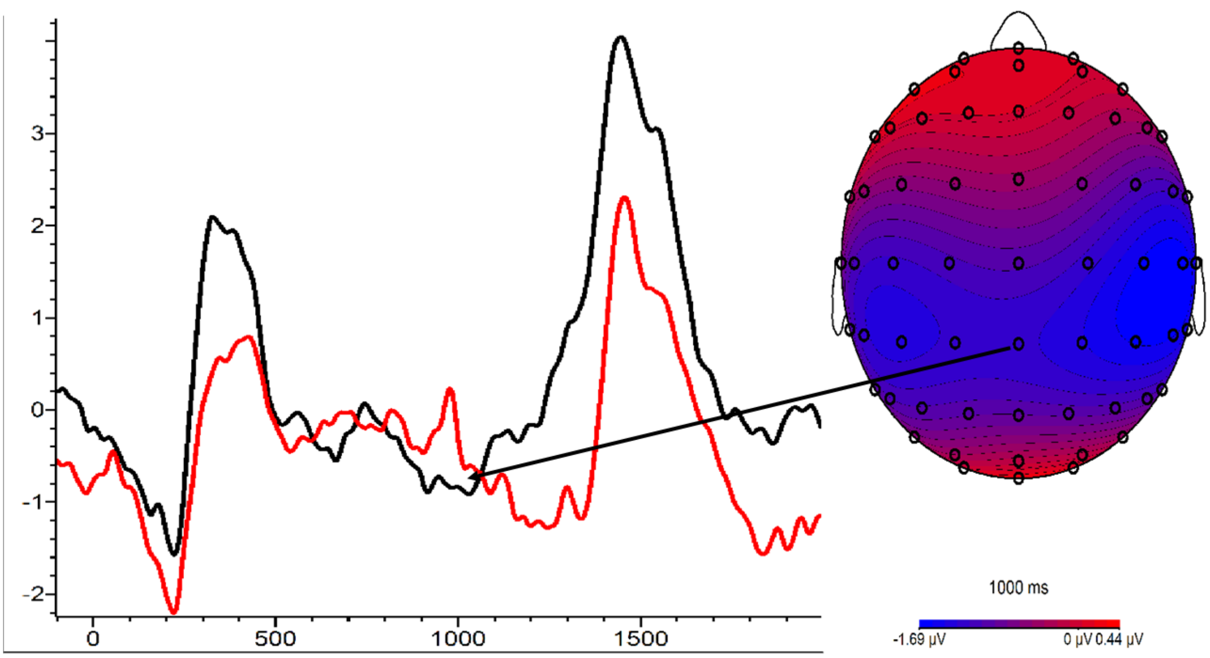

Figure 9. *Grand averaged ERP waveform with associated scalp topographies of the Cz electrode for the visual CTET.* Note. Colour coding: Black, hits; Red, misses. The epoch is -100ms to 2000ms relative to pre-target frame onset. The topographical map was observed at

1000ms as the collapsed localiser ERP waveforms showed the CNV peaks at ~1000ms across hits and misses. Analysis showed the CNV did not differ between hits and misses (p = .382).

Frontal and parietal P3

The late positive wave was assessed around its dominant peak during the 1300-1600ms interval at frontal and parietal electrode sites. Regarding the cluster analysis, RMs ANOVA (within factors: detection - hit and miss; region – frontal and parietal) revealed a main effect of detection, $F_{(1,14)} = 5.24$, $p = .038$, and a detection by region interaction effect, $F_{(1,14)} = 10.36$, $p = .006$. However, comparing hits and misses between each region showed a significant difference in the late positive wave at parietal sites only ($p < .001$; see figure 10).

Regarding the single-electrode analysis, RMs ANOVA (within factors: detection – hit and miss; region – frontal and parietal) revealed a main effect of detection, $F_{(1,14)} = 7.51$, $p = .016$, and a detection by region interaction effect, $F_{(1,14)} = 11.01$, $p = .005$. Comparing hits and misses between each region showed a significant difference in the late positive wave at parietal sites only ($p < .001$; see figure 10). Thus, both cluster and single-electrode analysis findings support previous research findings (Dockree et al., 2017; O'Connell et al., 2009).

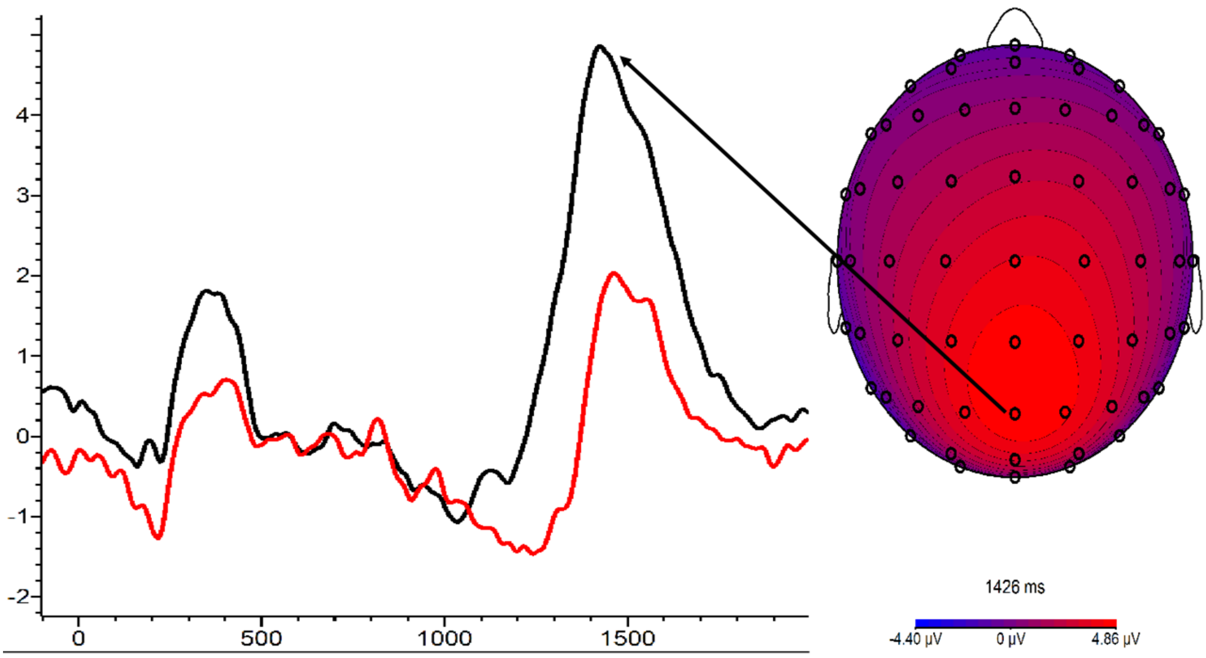

Figure 10. *Grand averaged ERP waveform with associated scalp topographies of the Pz electrode for the visual CTET.* Note. Colour coding: Black, hits; Red, misses. The P300 peaks at ~1400ms for both hits and misses but was significantly larger for hits compared to misses ($p < .001$).

However, grand average waveforms and topographical maps comparing hits and misses (see figure 11) during the immediate target processing period revealed a distinct positive wave over the frontocentral electrode sites around ~1200ms post pre-target frame onset for hits but not misses, indicating the presence of a frontal P3 during hits but not misses. Regarding the cluster analysis, RMs ANOVA revealed that the frontal P3 amplitude was marginally larger during hits compared to misses, $F_{(1,14)} = 3.87$, $p = .069$. Regarding the single-electrode analysis, paired sample t-tests findings showed the frontal P3 amplitude was significantly larger during hits ($M = 3.05$, $SD = 2.79$) compared to misses ($M = 1.37$, $SD = 2.78$), $t(14) = 2.57$, $p = .022$. Both findings extend previous research that found the frontal P3 to occur significantly earlier for hits compared to misses (O'Connell et al., 2009).

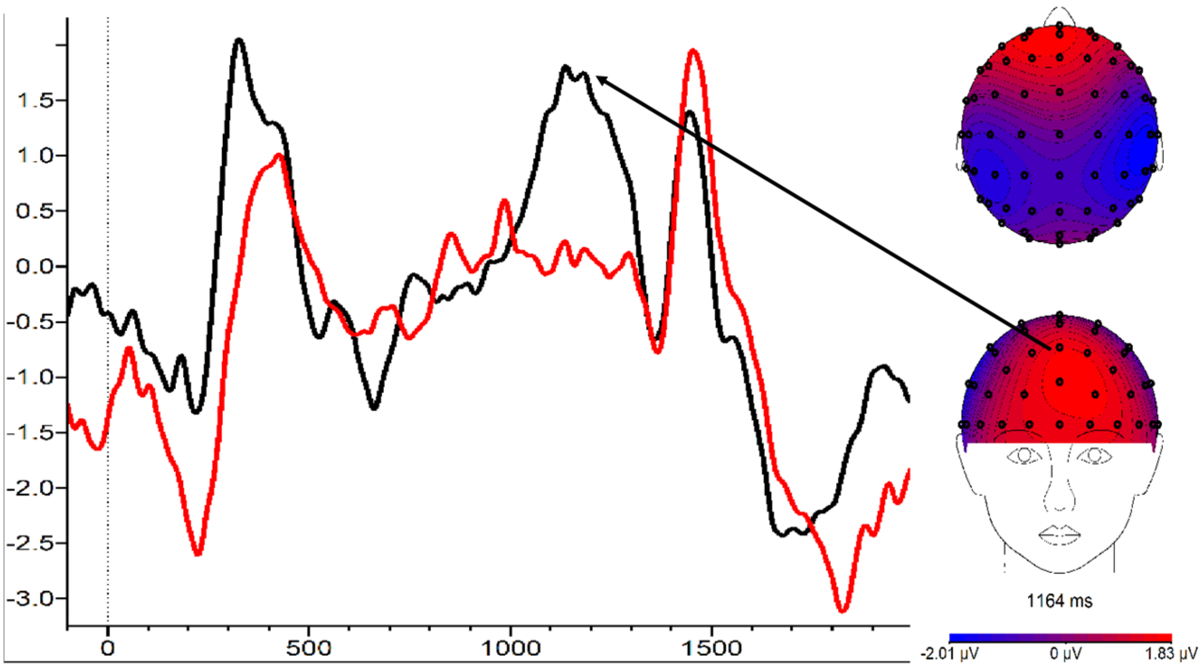

Figure 11. *Grand averaged ERP waveform with associated scalp topographies of the Fz electrode for the visual CTET.* Note. Colour coding: Black, hits; Red, misses. Both the waveforms and topographies display the occurrence of a frontal P3 during hits but not misses.

Visual ERP - Short term pre-target processing

N170

As stated previously, the N170 was only present at the Oz electrode, and as such, only single-electrode analysis was used to assess the N170. The N170 was measured from the Oz electrode site during the interval 140-220ms post frame onset. RMs ANOVA (within factors: detection – hit and miss; frame – pre-target, pre-target – 1, pre-target – 2, pre-target – 3, pre-target – 4) revealed a non-significant main effect of detection, $F_{(1,12)} = 1.21$, $p = .294$ (see figure 12), indicating no differences in N170 amplitude before hits or misses. Furthermore, analysis revealed a non-significant main effect of frame, $F_{(4,9)} = 1.36$, $p = .323$, and a non-significant interaction effect between detection and frame, $F_{(4,9)} = .49$, $p = .741$.

Thus, the results show that the N170 amplitude does not significantly differ between hits and misses during the pre-target frames, supporting previous research findings that early visual processing does not support visual sustained attention throughout the CTET (Dockree et al., 2017; O'Connell et al., 2009).

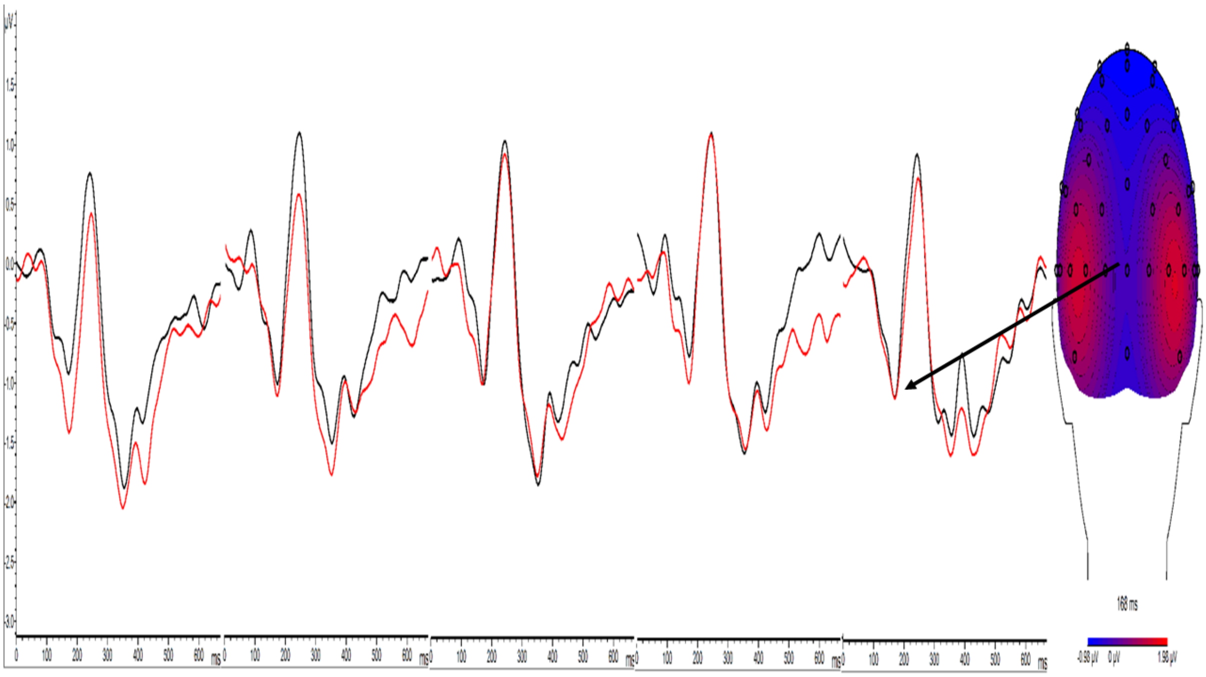

Figure 12. *Grand average ERP waveform of each pre-target frame for the visual CTET.*

Note. Hits are represented by the black line, misses are represented by the red line. This figure is displaying the)z electrode, frame order is pre-target – 4 (left) to pre-target (right).

Frontal P300

The frontal P3 was measured around the dominant peak at frontocentral electrode sites during the interval 280-400ms post frame onset. To assess the frontal P3 using the cluster analysis approach, RMs ANOVA (within factors: detection – hit and miss; frame – pre-target, pre-target – 1, pre-target – 2, pre-target – 3, pre-target – 4) revealed a non-significant main effect for detection, $F_{(1,12)}$ = 2.39, p = .148, indicating no differences in frontal P3 amplitude before hits or misses. Furthermore, analysis revealed a non-significant main effect of frame, $F_{(1,9)}$ = 1,53, p = .392, and a marginal significant interaction effect between detection and frame, $F_{(1,9)}$ = 2.79, p = .093. Further analysis per frame showed a main effect for detection during the pre-target frame only (p = .015), in that, the frontal P3 amplitude was significantly larger during hits compared to misses during the pre-target frame only.

Regarding the single-electrode analysis, RMs ANOVA (within factors: detection – hit and miss; frame - pre-target, pre-target – 1, pre-target – 2, pre-target – 3, pre-target – 4) revealed a non-significant main effect of detection, $F_{(1,12)} = 1.93$, $p = .19$, indicating no differences in frontal P3 amplitudes between hits and misses. Furthermore, analysis revealed a non-significant main effect of frame, $F_{(1,9)} = .82$, $p = .543$, and a non-significant interaction effect between detection and frame, $F_{(1,9)} = 2.26$, $p = .143$.

Surprisingly, these findings do not support consistent research findings that successfully detected targets elicit larger frontal P3 amplitudes up to 4 seconds before a target compared to an unsuccessful detection (Dockree et al., 2017; O'Connell et al., 2009).

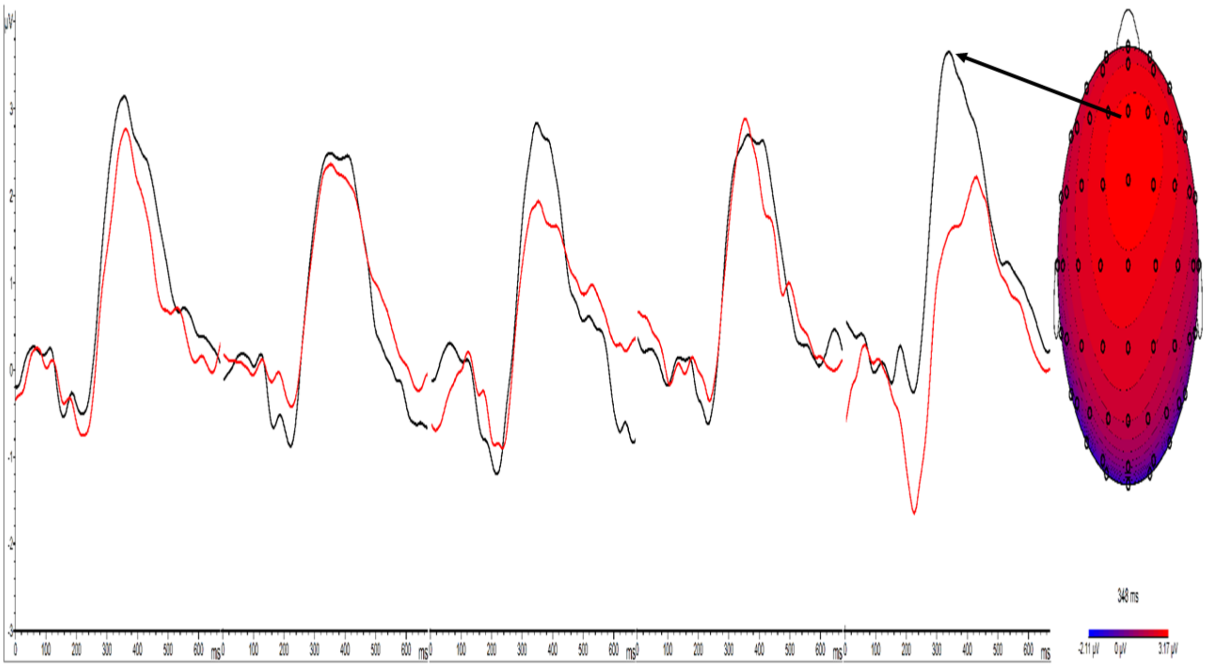

Figure 13. *Grand average ERP waveform of each pre-target frame for the visual CTET.* Note. Hits are represented by the black line, misses are represented by the red line. This figure is displaying the Fz electrode, frame order is pre-target – 4 (left) to pre-target (right).

Auditory ERP analysis – Immediate target processing

N100

The N1 was measured from a group of left and right central parietal electrodes during the 900-1000ms interval post pre-target frame onset. Regarding the cluster analysis, RMs ANOVA results revealed the N1 amplitude was significantly larger for hits compared to misses, $F_{(1,10)} = 42.12$, $p < .001$ (see figure 14). There was no main effect for region, $F_{(1,10)} =$

.1, p = .764. There was also no interaction effect between detection and region, $F_{(1,10)}$ = 1.75, p = .216.

Regarding the single electrode analysis, paired sample t-tests findings revealed the N1 amplitude was significantly larger for hits (CP3, M = 3.63, SD = 1.59; CP4, M = 3.59, SD = 1.66) compared to misses (CP3, M = 1.38, SD = 1.18; CP4, M = 1.15, SD = 1.67) at the CP3 electrode, $t(10)$ = -5.93, p < .001, and CP4 electrode, $t(10)$ = -4.03, p = 002. Both cluster and single-electrode analysis findings support our hypothesis that N1 amplitudes during the target interval will be significantly larger for hits compared to misses.

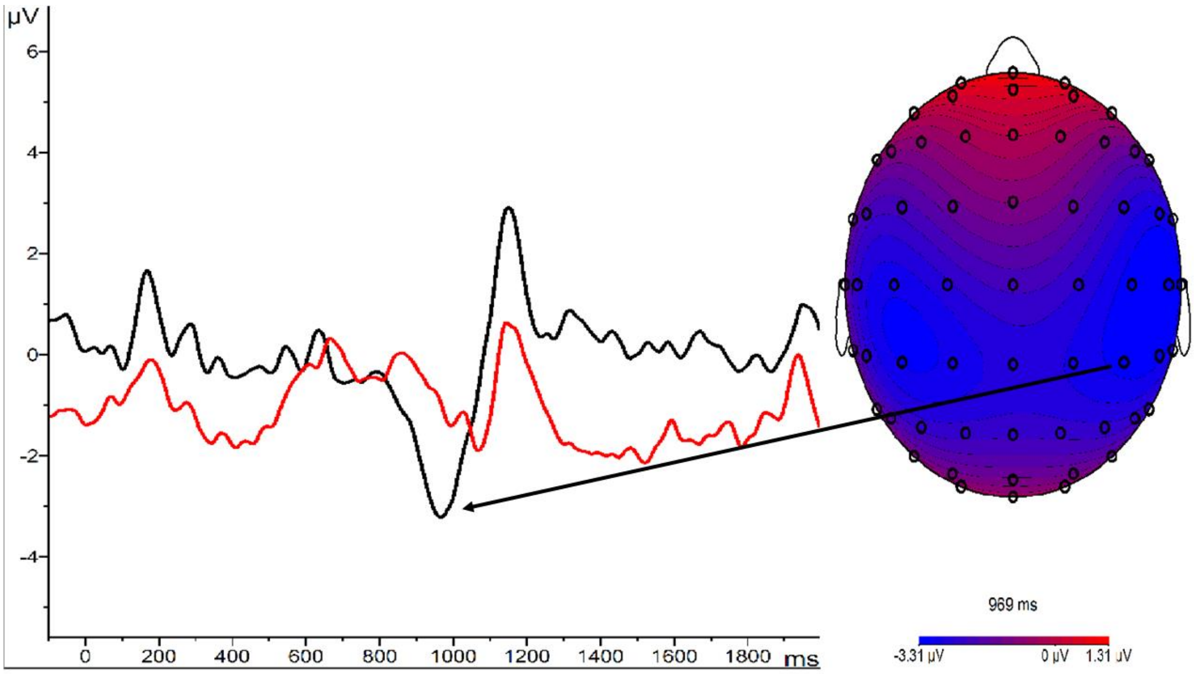

Figure 14. *Grand averaged ERP waveform with associated scalp topographies of the CP4 electrode for the auditory CTET.* Note. Colour coding: Black, hits; Red, misses. The N100 amplitude was significantly larger for hits compared to misses (p < .001).

Frontal and parietal P300

The late positive wave was assessed around the dominant peak at frontal and parietal regions. Regarding the cluster analysis, RMs ANOVA (within factors: detection- hit and miss; regions – frontal and parietal) revealed a marginal main effect for detection, $F_{(1,10)}$ = 3.36, p = .097, a main effect for region, $F_{(1,10)}$ = 5.83, p = .036, and a significant interaction effect between detection and region, $F_{(1,10)} = 9.94$, $p = .010$ (see figure 15). Further analysis revealed this late positive wave was significantly larger for hits compared to misses at parietal sites only ($p = .016$), which is consistent with findings from the visual post-target processing period.

Regarding the single-electrode analysis, RMs ANOVA (within factors: detection- hit and miss; regions – frontal and parietal) revealed a marginal main effect for detection, $F_{(1,10)} = 3.90$, $p = .077$, a main effect for region, $F_{(1,10)} = 7.72$, $p = .02$, and a significant interaction effect between detection and region, $F_{(1,10)} = 8.49$, $p = .015$ (see figure 13). Further analysis revealed this late positive wave was significantly larger for hits ($M = 5.54$, $SD = 2.85$) compared to misses ($M = 2.12$, $SD = 1.61$) at parietal sites only ($p = .009$).

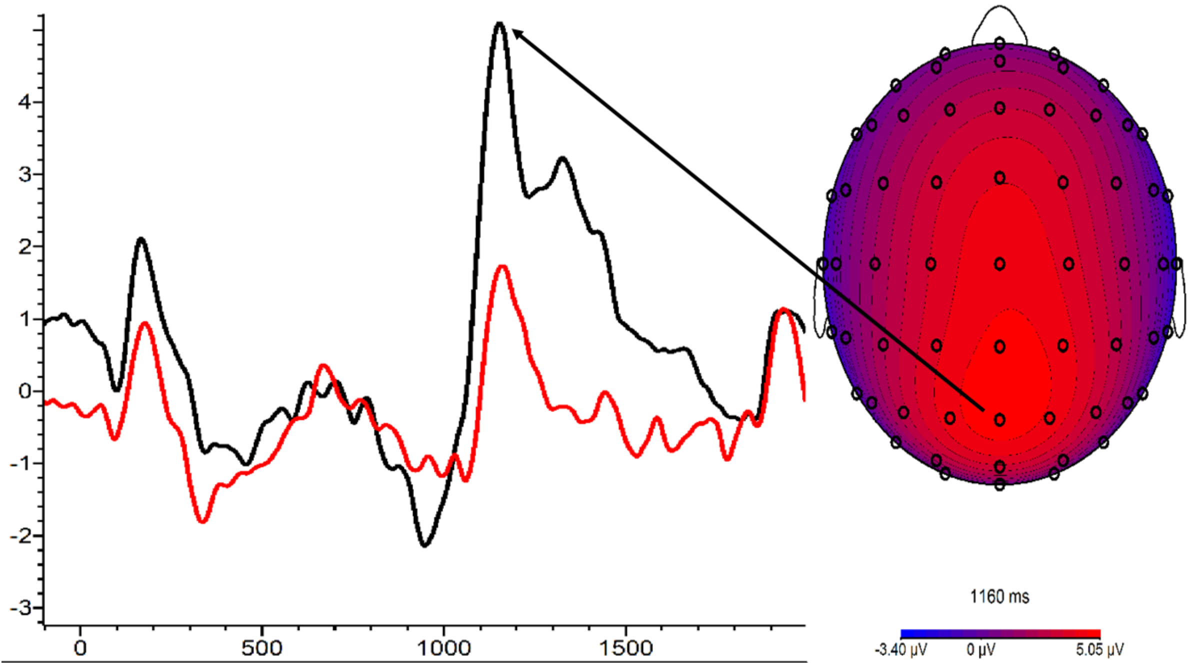

Figure 15. *Grand averaged ERP waveform with associated scalp topographies of the Pz electrode for the auditory CTET.* Note. Colour coding: Black, hits; Red, misses. The parietal P3 amplitude was significantly larger during hits compared to misses ($p = .016$) at parietal sites only.

However, as stated above, a separate second positive wave was observed over parietal sites, termed the parietal P3. Regarding the cluster analysis, RMs ANOVA showed that the parietal P3 amplitude was significantly larger during hits compared to misses, $F_{(1,10)} = 11.68$,

p = .007 (see figure 16). Regarding the single-electrode analysis, paired sample t-tests revealed that the parietal P3 was significantly larger (M = 3.64, SD = 3.36) compared to misses (M = .80, SD = 1.38), $t(10)$ = 2.83, p = .018).

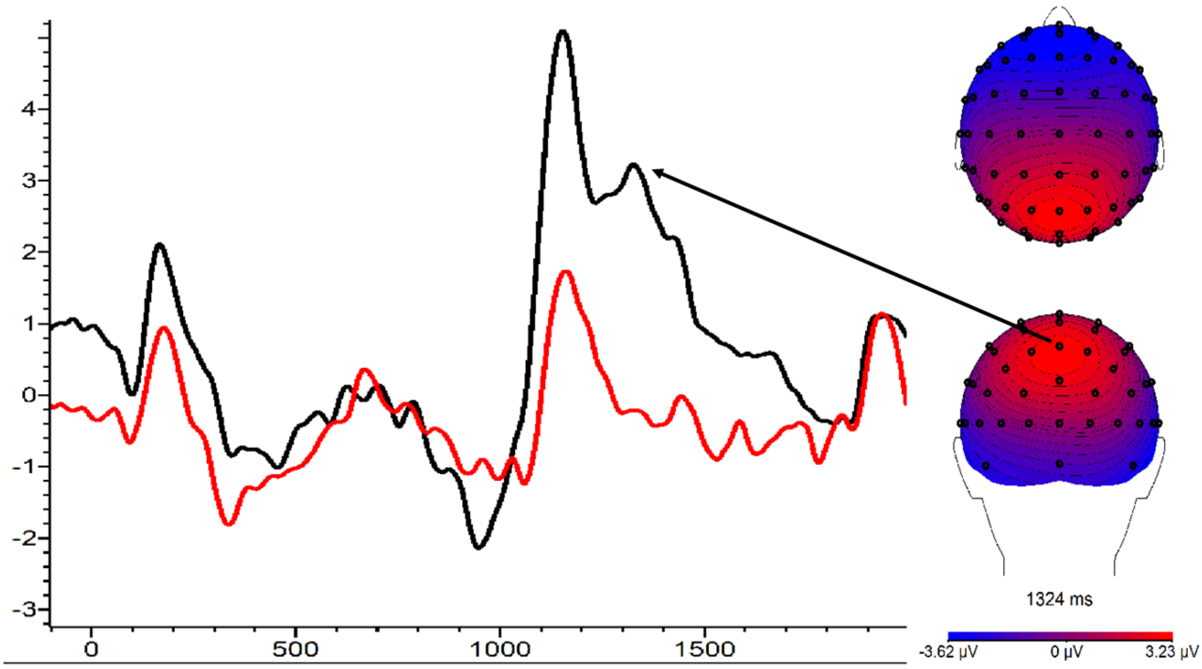

Figure 16. *Grand averaged ERP waveform with associated scalp topographies of the Pz electrode for the auditory CTET.* Note. Colour coding: Black, hits; Red, misses. The second late positive peak during hits occurs at ~1350ms, which was significantly larger compared to misses (p = .007).

Auditory ERP analysis – Short term pre-target processing

N100

The N1 was measured from a group of parietal electrodes during the 80-120ms interval post frame onset. Regarding the cluster analysis, RMs ANOVA (within factors: detection – hit and miss; frame – pre-target, pre-target – 1, pre-target – 2, pre-target – 3, pre-target – 4) revealed a non-significant main effect of detection, $F_{(1,10)}$ = 2.13, p = .176, a non-significant main effect for frame, $F_{(1.87,18.65)}$ = .66, p = .52, and no interaction effect between detection and frame, $F_{(4,40)}$ = 1.49, p = .223.

Regarding the single-electrode analysis, RMs ANOVA (within factors: detection – hit and miss; frame – pre-target, pre-target – 1, pre-target – 2, pre-target – 3, pre-target – 4) findings showed a marginal main effect of detection, $F_{(1,10)} = 3.75$, $p = .081$, a marginal main effect of frame, $F_{(2.60,25.96)} = 2.46$, $p = .091$, and a non-significant interaction effect between detection and frame, $F_{(4,40)} = 1.49$, $p = .224$. Thus, the results show that the N1 amplitude over the parietal region does not significantly differ between hits and misses during pre-target frames, indicating that exogenous attentional processing does not support auditory sustained attention throughout the CTET. These findings would support previous arguments that exogenous attentional processing does not support sustained attention during the CTET, and lapses of sustained attention primarily impact higher-order endogenous attentional processing.

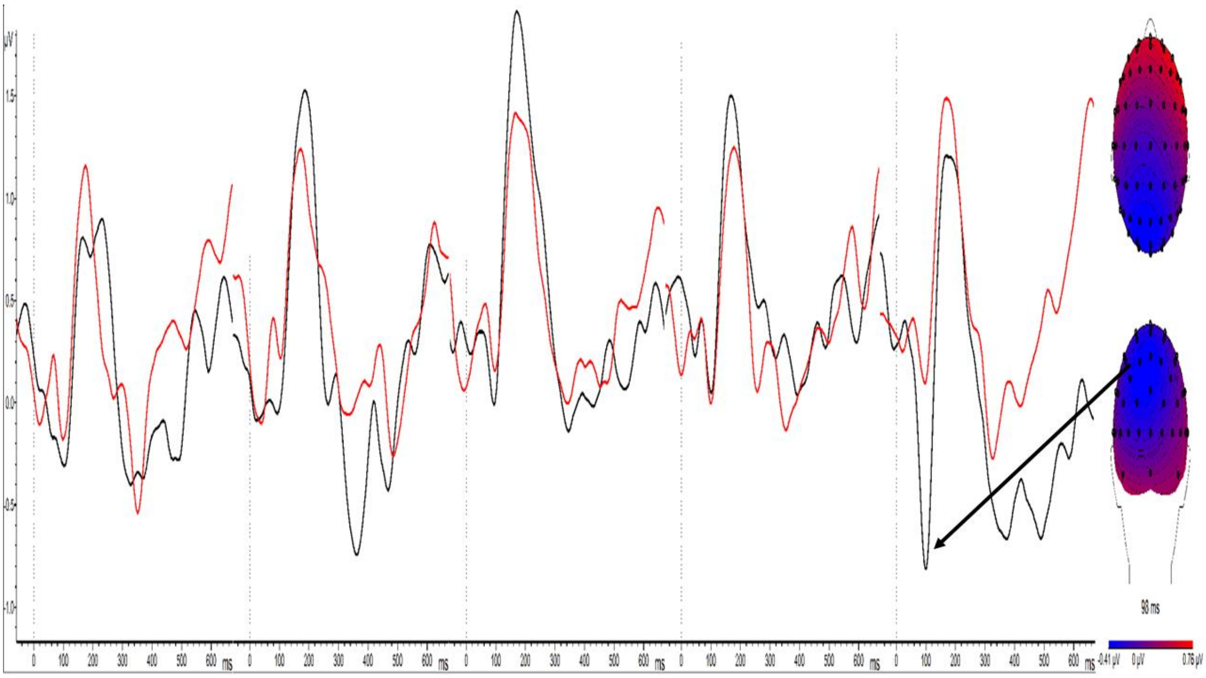

Figure 17. *Grand average ERP waveform of each pre-target frame for the auditory CTET.* Note. Hits are represented by the black line, misses are represented by the red line. This figure is displaying the Fz electrode, frame order is pre-target – 4 (left) to pre-target (right).

Frontal P300

The frontal P3 was measured from a group of frontocentral electrodes during the 120-220ms interval post frame onset. Regarding the cluster analysis, RMs ANOVA (within factors:

detection – hit and miss; frame – pre-target, pre-target – 1, pre-target – 2, pre-target – 3, pre-target – 4) revealed a significant main effect of detection, $F_{(1,10)} = 9.49$, $p = .012$ (see figure 18), a marginal main effect of frame, $F_{(1.21,12.16)} = 3.65$, $p = .074$, and a non-significant interaction effect between detection and frame, $F_{(1.43,14.28)} = .47$, $p = .572$.

Regarding the single electrode analysis, RMs ANOVA (within factors: detection – hit and miss; frame – pre-target, pre-target – 1, pre-target – 2, pre-target – 3, pre-target – 4) revealed a significant main effect of detection, $F_{(1,10)} = 9.60$, $p = .01$, no main effect of frame, $F_{(4,40)} = .80$, $p = .53$, and a marginal interaction effect between detection and frame, $F_{(4,40)} = 2.08$, $p = .10$. Further analysis showed per frame showed a main effect for detection during pre-target – 1 ($p < .001$), pre-target – 2 ($p = .011$), pre-target – 3 ($p = .004$), and pre-target – 4 ($p = .011$) frames, and the pre-target frame showed a marginal significant effect for detection ($p = .061$).

Thus, ANOVA results show that the frontal P3 amplitude is significantly larger over the frontocentral region prior to a hit compared to a miss, indicating that the frontal P3 has predictive characteristics of lapses in auditory sustained attention. These findings are similar to previous research findings within the visual modality (Chidharom et al., 2021; Dockree et al., 2017; O’Connell et al., 2009).

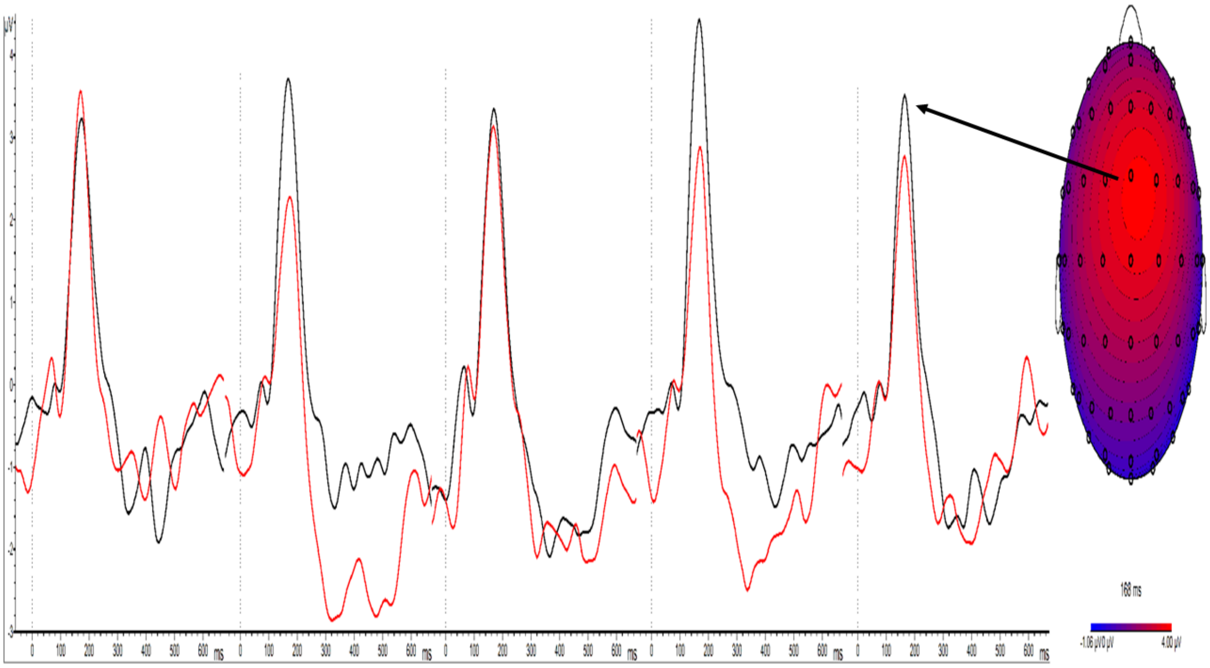

Figure 18. *Grand average ERP waveform of each pre-target frame for the auditory CTET.*

Note. Hits are represented by the black line, misses are represented by the red line. This figure is displaying the FCz electrode, frame order is pre-target – 4 (left) to pre-target (right).

Discussion

The present study provides the first evidence that lapses of auditory sustained attention can be predicted by altered electrophysiological activity up to 4 seconds prior to a lapse. First, this study did not support previous research findings showing lapses of visual sustained attention is associated with reduced frontal P3 amplitudes up to 4 seconds prior to a lapse (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). However, in accordance with our hypotheses, this study did find evidence that lapses of auditory sustained attention are associated with reductions in frontal P3 amplitude during the preceding non-target frames prior to a lapse, whereas N1 amplitudes during the preceding non-target frames prior to a lapse were not associated with lapses of auditory sustained attention. Furthermore, this study observed similar downstream effects of auditory and visual sustained attention (i.e., the activity during the time period after a target is presented). Specifically, successful target detection is associated with an increase in frontal and parietal P3 amplitudes relative to unsuccessful target detection across modalities. Also, successful target detection during the auditory CTET led to an increase in N1 amplitudes relative to unsuccessful target detection.

This study was the first to examine the shared and distinct electrophysiological substrates associated with lapses of sustained attention across modalities. Previous research that has examined the neural substrates associated with sustained attention has focused on the visual modality, indicating that lapses of sustained attention can be predicted by altered frontal P3 activity up to 4 seconds prior to the lapse (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). These findings have been further supported through pharmacological studies and extended to show methylphenidate (MPH), a drug known to reduce attentional deficits and used to treat attention-related disorders such as ADHD, can induce a linear increase in frontal P3 amplitude during the pre-target period (Dockree et al., 2017). Furthermore, group comparison research has shown schizophrenic patients, known to display attentional deficits compared to healthy controls, show altered frontal P3 activity during the pre-target period prior to a lapse of visual sustained attention. This body of research has led researchers to suggest that this frontal P3 component represents a time monitoring mechanism that can track the temporal structure of the CTET, and this mechanism is likely governed by endogenous (top-down) attentional processing. However, to date, only behavioral research has examined lapses of auditory sustained attention (Berry et al., 2014).

Although this study did not replicate previous research findings regarding visual sustained attention, our findings show that lapses of auditory sustained attention are foreshadowed by reductions in frontal P3 amplitude. This extends previous research findings to suggest that the frontal P3 is a neural mechanism that displays predictive characteristics of lapses of sustained attention across modalities, both auditory and visual. Due to previous findings showing lapses of visual sustained attention are not associated with well-supported indices of bottom-up visual processing, the P1 and SSVEP, researchers suggest this frontal P3 component reflects endogenous attentional processing that monitors the temporal structure of the task. In a similar manner, this study provides further premise that the frontal P3 component may reflect endogenous attentional processing through our findings of the N1.

Auditory oddball studies have shown that during attentional processing, the neural intracranial generator of the N1 is modulated by the state of listening. LORETA findings show during passive listening conditions, the N1 can be sourced to the auditory cortex and multisensory association areas. However, during active listening conditions, the N1 can be sourced to the VAN, specifically, the IPL (Justen & Herbert, 2018). As such, during active listening conditions the N1 likely reflects exogenous attentional processing. This study found no association between N1 activity and lapses of auditory sustained activity during the pre-target period. Thus, this study suggests that similarly to visual sustained attention, early sensory evoked potentials do not differentiate between successful and unsuccessful auditory target detection during the pre-target period. As such, within the context of this study, these findings provide further support that lapses of sustained attention during a CTET paradigm primarily impact endogenous attentional processes, and not exogenous attentional processing (O'Connell et al., 2009). Also, it is likely that these findings are in line with previous auditory oddball LORETA findings (Justen & Herbert, 2018), in that, late-stage ERP components (e.g., frontal and parietal P3) during attentional processing are governed by activity within the DAN (dorsal attention network).

As discussed previously, Polich's (2007) cognitive model hypothesizes that the frontal P3 serves to inhibit extraneous neural activity to facilitate the initiation of neural activity within the parietal areas associated with working memory processing, which leads to the production of the parietal P3. Polich's (2007) argument that a frontal P3 is elicited when attention demanding stimuli differ from the contents of working memory was based on EEG findings from oddball paradigms. However, as shown in this study and previous sustained attention research, the presence of a frontal P3 during the pre-target frames and the absence of a stimulus change during the target interval in the CTET would dispute Polich's argument. As discussed previously, due to the design of auditory oddball experiments, exogenous attentional processes at the onset of each trial are sufficient to support successful target discrimination (Justen & Herbert, 2018; Näätänen et al., 2007). Also, meta-analysis research of oddball fMRI findings has shown the inferior frontal junction, a brain region that is said to play a functional interaction role between the VAN and DAN (Fox et al., 2006), displays greater activation during oddball stimuli compared to standard stimuli. The author of the meta-analysis study suggests this may reflect greater functional interaction between the DAN and VAN during oddball compared to standard stimuli (Kim et al., 2014), which would be in line with research showing dorsal (endogenous) and ventral (exogenous) attention networks do not work in isolation, but rather flexibly interact with each other to enable dynamic control of attention in relation to current environmental demands (Vossel et al., 2014).

Given this body of research, and the findings regarding frontal P3 activity observed during the auditory and visual CTET, this paper posits that the frontal P3 is an endogenous attention mechanism that will be elicited whenever endogenous attentional processes are actively engaged and carry out top-down inhibition of extraneous neural activity. By extension, this argues that a frontal P3 can be elicited in the absence of the presentation of an attention demanding stimulus that differs from the contents of working memory.

Sustained attention research has employed the visual CTET (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009) and Mackworth Clock Test (Martel et al., 2014) to show a frontal P3 component is elicited after the onset of every trial, target or non-target, and this frontal P3 is associated with lapses of sustained attention. Similarly, our findings show that this frontal P3 can sufficiently predict lapses of auditory sustained attention prior to a lapse, supporting previous findings and interpretations that the frontal P3 is an endogenous attentional mechanism that can track the temporal structure of the CTET (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). Furthermore, similar to visual CTET findings, our findings show a frontal P3 is elicited in the absence of any stimulus change during the target interval of the auditory CTET. Also interestingly, our findings show that during the target interval of the visual CTET, a frontal P3 was present for hits, but was absent for misses (see figure 11). This may indicate that during the target interval of missed targets, endogenous attentional resources have been exhausted and no inhibition of extraneous neural activity occurred, explaining the lack of frontal P3 during the target interval of missed targets.

Within the context of an auditory oddball paradigm, this hypothesis would suggest that if a non-target is presented, the functional interaction between the VAN (exogenous) and DAN (endogenous) via the IFJ may determine that top-down (endogenous) inhibition of extraneous neural activity is not required during each non-target trial, which results in the absence of a frontal P3 during the non-target frames of an auditory oddball paradigm. As such, during the non-target trial of an auditory oddball paradigm, the absence of a frontal P3 indicates that endogenous attentional processes are not actively inhibiting extraneous neural activity to facilitate the initiation of neural activity within the parietal areas associated with memory processes (Wessel & Aron, 2013). Also, this would be in line with findings that exogenous attentional processes are sufficient in discriminating a target from a non-target trial during an auditory oddball paradigm (Justen & Herbert, 2018; Näätänen et al., 2007). The absence of a frontal P3 during the non-target trials of an auditory oddball paradigm does not reflect whether a stimulus change occurred, as argued in the context updating theory of the P300 (Polich, 2007).

A possible route for future research to further examine this hypothesis would be to employ the auditory CTET from Berry et al., (2014), which uses a single 500Hz square tone for both target and non-target trials. This study would argue that a frontal P3 would be elicited after each pre-target frame as observed in other CTET paradigms, which would reflect the active engagement of endogenous attentional processes in inhibiting extraneous neural activity to facilitate sustained attentional processing. Whereas Polich's (2007) theory would expect no frontal P3 to be elicited after each pre-target frame as the attention demanding stimulus would not differ from working memory.

Regarding our replication hypotheses for the visual CTET, although within this dataset frontal P3 amplitudes showed a trend of decreasing prior to a lapse of visual sustained attention, this study did not support previous research findings that lapses of visual sustained attention are foreshadowed by a reduction in frontal P3 amplitudes 4 seconds prior to a lapse (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). However, cluster analysis findings of the frontal P3 did show a marginal interaction effect between detection and frame, which revealed that lapses of visual sustained attention were associated with reductions in frontal P3 amplitudes during the pre-target frame only (see figure 11). Albeit, these findings were not replicated through the single-electrode analysis findings.

There are two factors that may have affected the ability to replicate previous research findings from the visual CTET. First, this study employed both an auditory and visual CTET within the same session. This study did counterbalance the order of the tasks to eliminate task-order effects. However, Berry et al., (2014) had participants complete either the auditory or visual CTET and found time-on-task performance decline is significantly steeper for the visual CTET compared to the auditory CTET. Thus, although this study did counterbalance to eliminate possible task-order effects, it is possible that visual endogenous attentional resources are more sensitive to exhaustion compared to auditory endogenous attentional resources, and as such, completing the visual CTET after the auditory CTET within the same session may not have the same behavioral and neural consequences to completing the visual CTET within a separate session. Interestingly, of the 15 participants who displayed H/FA rates above 3 for the visual CTET, 11 (73.33%) of those completed the visual task first, whereas of the 13 participants who displayed H/FA rates above 3 for the auditory CTET, only 6 (46.15%) of those completed the auditory task first.

Future studies should incorporate a 2-day protocol, in which participants complete the auditory and visual CTET on separate days. This would eliminate the possibility of potential differences in the top-down attentional resources available at the start of each task and the sensitivity of top-down attentional resources to exhaustion across modalities (Berry et al., 2014). Given that the frontal P3 amplitude is said to be modulated by the level of endogenous attentional resources available (O'Connell et al., 2009), and MPH can induce a linear increase in frontal P3 amplitudes during the pre-target period (Dockree et al., 2017), it is possible that this study was not able to replicate previous findings due to differences in experimental design impacting endogenous attentional resources (i.e., 2 CTETs performed vs 1 CTET performed).

Secondly, due to technical errors, the version of the visual CTET employed here presented stimuli with a 10Hz flicker instead of previously used 25Hz. In layman's terms, this means that the presented image was refreshed at a rate of 100ms every second, compared to 40ms every second in previous research (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). Given that the refresh rate was very low, this may have affected the precise timing of frame onset and also participants ability to distinguish the exact point of frame onset for each trial, which may cause difficulty in perceiving the onset of a new visual stimulus. Considering the task goal was to determine and compare the temporal duration of each stimulus, and the frontal P3 is said to monitor and track the temporal structure of the task, the alterations to the visual CTET in the present study make it difficult to oppose consistent previous research findings (Chidharom et al., 2021; Dockree et al., 2017;

O'Connell et al., 2009). The alterations to the visual CTET may also explain the unexpected absence of a P1 component during the visual CTET (see figure 6).

Previous research has consistently observed a P1 at the start of each standard frame of the visual CTET, and have used this index of basic visual processing to show lapses of visual sustained attention are not associated with visual perceptual analysis (O'Connell et al., 2009). In appearance, the lack of a visual P1 would indicate that there was an absence of visual processing during the visual CTET, or potentially a difficulty in distinguishing the onset of a new visual stimulus. However, a N170 component is present over the Oz electrode during the pre-target frames (see figure 12). The N170 has been consistently linked to visual object processing (Rossion et al., 2000) and has shown to be face sensitive (Hadjikhani et al., 2009; Itier & Taylor, 2004). This study showed that N170 amplitudes during the pre-target period did not differ between successful and unsuccessful target detection, supporting previous literature that basic visual processing (P1 and SSVEP) is not associated with lapses of visual sustained attention during the visual CTET (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009).

However, this is the first study to observe no visual P1 during the visual CTET while using a different SSVEP frequency tag. Previous research has shown that the visual spatial attentional effects of the SSVEP and transient ERPs reflect complementary aspects of spatial attention (Müller & Hillyard, 2000), and the choice of flicker frequency can modulate which cortical network synchronizes to the flicker (Ding et al., 2005). Thus, it is possible that using a distinct SSVEP frequency tag compared to previous research caused a distinct pattern of bottom-up visual processing during attentional processing compared to previous research (O'Connell et al., 2009). Future research should examine whether different SSVEP frequency tags have distinct effects on the neural underpinning of sustained attention.

Limitations and future directions

Although this study was the first to examine the shared and distinct neural mechanisms associated with lapses of sustained attention across modalities, some limitations need to be addressed. Although this study added valuable insight into an emerging line of research (i.e., lapses of sustained attention), the sample size was relatively small compared to previous sustained attention research (Brosnan et al., 2018; Chidharom et al., 2021; Dockree et al., 2017; Irrmischer et al., 2018; O'Connell et al. 2009). All previous research that has assessed the neural substrates associated with the visual CTET have used much larger sample sizes (*N* = 56, 22, 40, 57, 29; order respective to previous in-text citation) and only one CTET paradigm.

As discussed previously, past research has suggested modality differences in the exhaustion of endogenous attentional resources, in which attentional resources deplete significantly more across the visual compared to the auditory CTET (Berry et al., 2014). Future research should aim to assess visual and auditory sustained attention in a 2-day protocol; this would allow for the direct comparison of the shared and distinct neural substrates associated with lapses of sustained attention across modalities, while removing for any confounding effects caused by potential differences in the endogenous attentional resources available at the start of each task.

Lastly, regarding the visual CTET, due to a technical error this study employed a SSVEP with a distinct frequency tag compared to previous research (10Hz vs 25Hz). This may have confounded the neural activity modulated by attentional effects, which could explain the lack of support for previous research findings (Chidharom et al., 2021; Dockree et al., 2017; O'Connell et al., 2009). Regarding the limitations of the auditory CTET, from the participant feedback after the task, some participants noted that the highest pitch (875Hz tone) felt more salient compared to the other tones. Although these participants ensured the difference in perceptual salience did not affect their ability to perform the task, and electrophysiological research has shown no statistical differences in ERP amplitude or latency between tonal frequencies below 1000Hz (Picton et al., 1978; Polich et al., 1985; Teichert, 2016), future versions of the auditory CTET may benefit from using 4 different tonal frequencies below the Hz level of the third highest pitched tone used in the auditory CTET paradigm employed in this study (750Hz).

Regarding the future directions of this research, and interesting avenue may be to examine the relationship between the frontal P3 and alpha oscillatory activity with the auditory and visual CTET. As stated previously, this study and previous research has shown the effects of sustained attention on the frontal and parietal P3. However, research findings have also shown that maladaptive increases in posterior alpha oscillatory activity is strongly associated with lapses of visual sustained attention during the CTET (O'Connell et al., 2009). Furthermore, this maladaptive posterior alpha synchronization during the pre-target period is reduced by MPH to support visual sustained attentional processing (Dockree et al., 2017). Oddball research has shown a potentially functional relationship between the parietal P3 and alpha oscillatory activity. Peng et al., (2012) examined the relationship between parietal P3 and alpha event-related desynchronization (ERD) elicited by stimuli across four sensory modalities (auditory, visual, somatosensory, and pain). Their findings revealed that during target presentation across all sensory modalities, scalp topographies and cortical sources of the parietal P3 and alpha ERD were similar, whereas during non-target presentation, alpha ERD differed across modalities. The authors state their findings indicate that the parietal P3 and alpha ERD are independent of stimulus modality, and may reflect task-related higher order cognitive activation and attentional processing. Furthermore, effective connectivity analysis during target presentation showed cortical information flowed from alpha ERD to parietal P3 cortical sources. The authors suggest their findings reflect that the parietal P3 observed during presentation of targets during an oddball paradigm is modulated by alpha

ERD, which would support previous accounts of the association between the parietal P3 and alpha desynchronization (Polich, 2007). However, the relationship between the frontal P3 and alpha oscillatory activity is still unknown. Given our arguments that the frontal P3 is elicited by endogenous attentional processes actively engaged in top-down inhibition of extraneous neural activity, and the close relationship between alpha oscillatory activity and inhibition (Knyazev, 2007), future research should examine the relationship between the frontal P3 and alpha oscillatory activity with the auditory and visual CTET.

To conclude, the present study aimed to examine the shared and distinct neural substrates that are associated with lapses of auditory and visual sustained attention. Overall, the present study suggests that lapses of sustained attention across modalities can be predicted by the same neural mechanism, the frontal P3. Furthermore, this study critiques previous theoretical accounts of the frontal P3 (Polich, 2007), providing evidence to suggest within the context of attentional processing, the frontal P3 is elicited when endogenous attentional processes are actively engaged and carrying out top-down inhibition of extraneous neural activity, regardless of the stimulus presentation.

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Appendix A

Stimuli presentation calibration

Due to the nature of EEG systems, there will always be a slight time delay between stimulus presentation and the timepoint of the stimulus marker on the EEG signal via the parallel port system. In order to ensure this time delay would not differ significantly between stimulus modality (visual frame vs auditory tone), both versions of the CTET were calibrated. To carry this out, an auditory and visual timing devices were used to assess when stimulus presentation occurred by recording the change in light energy from the screen (indicating visual stimulus presentation) or recording an input of auditory input. When the timing devices received an input, it sends a marker to the EEG signal via the parallel porting system. The whole duration of this process takes 79uS. Thus, the duration of the time it takes to send a marker to the EEG signal to mark stimulus presentation is 79uS, less than a millisecond.

The second timing process to consider is the delay between the timepoint at which PsychoPy is designated to produce a visual/auditory stimulus, and the timepoint at which it is actually presented to the participant. According to a study that examined the timing precision of various stimulus presentation programs across several processes, PsychoPy is one of the best performing programs (Bridges et al., 2020). This study used Psychtoolbox to produce audio tones and PyschoPy to produce the visual stimuli, both with Windows 10 computer system. According to Bridges et al., (2020) findings, the time delay between program production of visual stimuli and the stimulus marker timepoint on the EEG signal will be on average 7.1ms, and for auditory stimulus this time delay will be on average 0.77ms.

Thus, overall, the calibration sessions showed synchronizing the timing of the stimulus markers on the EEG signal and the actual timing of stimulus presentation would have an error rate of a few milliseconds for the visual stimuli and less than a millisecond for the auditory stimuli.

Appendix B

Auditory CTET history tree

Immediate target processing

Change sampling rate

Conversion is based on spline interpolation.

New Sampling Rate [Hz]: 256

New Sampling Interval [µS]: 3906.25

Data was filtered before downsampling with 115.2Hz, 24dB/oct.

Mastoid & Eye formula (EXG3 = Below eye, EXG4 = above eye)

The following formulas were calculated:

Mastoid_average = (EXG1+EXG2)/2   Unit: µV

VEOG = EXG4-EXG3   Unit: µV

HEOG = EXG6-EXG5   Unit: µV

The remaining channels were kept.

The new channels are on top.

Mastoid reference

Selected channels to include into the new reference:

Mastoid_average

The implicit reference is included in the calculation of the new reference.

Channels to which the new reference applies to:

AF3 AF4 AF7 AF8 AFz C1 C2 C3 C4 C5

C6 CP1 CP2 CP3 CP4 CP5 CP6 CPz Cz F1

F2 F3 F4 F5 F6 F7 F8 FC1 FC2 FC3

FC4 FC5 FC6 FCz Fp1 Fp2 Fpz FT7 FT8 Fz

Iz O1 O2 Oz P1 P10 P2 P3 P4 P5

P6 P7 P8 P9 PO3 PO4 PO7 PO8 POz Pz

T7 T8 TP7 TP8

Remaining (non rereferenced) channels are kept.

Name of the new reference channel: Avg

Filters

Zero phase shift Butterworth filters.

Global filter settings:

Low cutoff: 0.5305164 Hz, time constant 0.3, order 2

High cutoff: 40 Hz, order 2

Notch filter: 50 Hz

Segmentation

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 72

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: -3200.00 ms, End: 3000.00 ms, Length: 6200.00 ms

Allow overlapped segments? Yes

Skip bad intervals? No

Data was not stored but will be calculated on demand.

*** Data node specific information ***

Number of segments: 203

Baseline correction

Begin: 600 [ms]

End: 700 [ms]

Artifact rejection

Used Channels: 64

AF3	AF4	AF7	AF8	AFz	C1	C2	C3	C4	C5	C6	CP1	CP2
	CP3	CP4	CP5	CP6	CPz	Cz	F1	F2	F3	F4	F5	F6
	F7	F8	FC1	FC2	FC3	FC4	FC5	FC6	FCz	Fp1	Fp2	Fpz
	FT7	FT8	Fz	Iz	O1	O2	Oz	P1	P10	P2	P3	P4
	P5	P6	P7	P8	P9	PO3	PO4	PO7	PO8	POz	Pz	T7
	T8	TP7	TP8									

Check Gradient:

Maximal allowed voltage step: 50 µV/ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Difference (Max-Min):

Maximal allowed difference of values in intervals: 200 µV

Interval Length: 200 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Amplitude:

Minimal allowed amplitude: -200 µV

Maximal allowed amplitude: 200 µV

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Low Activity:

Lowest allowed activity in intervals: 0.5 µV

Interval Length: 100 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

*** Data node specific information ***

<u>Ocular Correction ICA</u>

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Horizontal activity channel: HEOG.

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Data used for ICA: Whole data.

Number of ICA steps: 512.

Convergence bound: 1E-07.

Bound number of considered blinks at 60.

ICA algorithm used: Infomax Restricted.

Channels enabled for ICA:

Mastoid_average VEOG HEOG Fp1 AF7

AF3 F1 F3 F5 F7

FT7 FC5 FC3 FC1 C1

C3 C5 T7 TP7 CP5

CP3 CP1 P1 P3 P5

P7 P9 PO7 PO3 O1

Iz Oz POz Pz CPz

Fpz Fp2 AF8 AF4 AFz

Fz F2 F4 F6 F8

FT8 FC6 FC4 FC2 FCz

Cz C2 C4 C6 T8

TP8 CP6 CP4 CP2 P2

P4 P6 P8 P10 PO8

PO4 O2 EXG1 EXG2 EXG3

EXG4 EXG5 EXG6 EXG7 EXG8

Status

<u>Target blink detection</u>

*** Artifact Rejection - Automatic Inspection ***

Used Channels: 1

VEOG

Check Gradient:

Maximal allowed voltage step: 200 µV/ms

Mark as Bad: Before Event: 1000 ms After Event: 200 ms

Check only Intervals in Segments:

Segment No.: IntervalStart [ms]: IntervalLength [ms]:

0 - 203 -3200 6199

<u>8Hz Low Pass filter</u>

*** IIR Filters ***

Zero phase shift Butterworth filters.

Global filter settings:

Low Cutoff: ---

High cutoff: 8 Hz, order 2

Notch filter: ---

<u>Import markers</u>

<u>Segmentation – hits</u>

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 98

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: -100.00 ms, End: 2000.00 ms, Length: 2100.00 ms

Allow overlapped segments? No

Skip bad intervals?   Yes

Data was not stored but will be calculated on demand.

*** Data node specific information ***

Number of segments: 36 (This is only for participant 1)

<u>Segmentation – misses</u>

Same as above for Segmentation – hits (but use S 99 instead of S 98).

<u>Average – hits</u>

<u>Average – misses</u>

<u>Peak detection</u>

*** Peak Detection ***

Automatic detection

Separate search for every channel

Local maxima was searched.

Short term pre-target processing

Same pre-processing steps as the Immediate target processing up until the first Segmentation.

Segmentation

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 72

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: -3400.00 ms, End: 800.00 ms, Length: 4200.00 ms

Allow overlapped segments? Yes

Skip bad intervals? No

Data was not stored but will be calculated on demand.

Segmentation (target – 1, target – 2, target – 3, target – 4)

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 72

Advanced Boolean Expression:

Baseline correction

*** Baseline Correction Transformation ***

Begin: -78.125 [ms]

End: 0 [ms]

Artifact rejection

Used Channels: 64

AF3	AF4	AF7	AF8	AFz	C1	C2	C3	C4	C5	C6	CP1	CP2
	CP3	CP4	CP5	CP6	CPz	Cz	F1	F2	F3	F4	F5	F6
	F7	F8	FC1	FC2	FC3	FC4	FC5	FC6	FCz	Fp1	Fp2	Fpz
	FT7	FT8	Fz	Iz	O1	O2	Oz	P1	P10	P2	P3	P4
	P5	P6	P7	P8	P9	PO3	PO4	PO7	PO8	POz	Pz	T7
	T8	TP7	TP8									

Check Gradient:

Maximal allowed voltage step: 50 µV/ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Difference (Max-Min):

Maximal allowed difference of values in intervals: 200 µV

Interval Length: 200 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Amplitude:

Minimal allowed amplitude: -200 µV

Maximal allowed amplitude: 200 µV

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Low Activity:

Lowest allowed activity in intervals: 0.5 µV

Interval Length: 100 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

*** Data node specific information ***

Ocular Correction ICA

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Horizontal activity channel: HEOG.

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Data used for ICA: Whole data.

Number of ICA steps: 512.

Convergence bound: 1E-07.

Bound number of considered blinks at 60.

ICA algorithm used: Infomax Restricted.

Channels enabled for ICA:

Mastoid_average VEOG HEOG Fp1 AF7

AF3 F1 F3 F5 F7

FT7 FC5 FC3 FC1 C1

C3 C5 T7 TP7 CP5

CP3 CP1 P1 P3 P5

P7 P9 PO7 PO3 O1

Iz Oz POz Pz CPz

Fpz Fp2 AF8 AF4 AFz

Fz F2 F4 F6 F8

FT8 FC6 FC4 FC2 FCz

Cz C2 C4 C6 T8

TP8 CP6 CP4 CP2 P2

P4 P6 P8 P10 PO8

PO4 O2 EXG1 EXG2 EXG3

EXG4 EXG5 EXG6 EXG7 EXG8

Status

Target blink detection

*** Artifact Rejection - Automatic Inspection ***

Used Channels: 1

VEOG

Check Gradient:

Maximal allowed voltage step: 200 µV/ms

Mark as Bad: Before Event: 1000 ms After Event: 200 ms

Check only Intervals in Segments:

Segment No.: IntervalStart [ms]: IntervalLength [ms]:

0 - 203 -3200 6199

8Hz Low Pass filter

*** IIR Filters ***

Zero phase shift Butterworth filters.

Global filter settings:

Low Cutoff: ---

High cutoff: 8 Hz, order 2

Notch filter: ---

<u>Import markers</u>

<u>Segmentation – hits</u>

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 98

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: 0.00 ms, End: 600.00 ms, Length: 600.00 ms

Allow overlapped segments? No

Skip bad intervals? Yes

Data was not stored but will be calculated on demand.

<u>Segmentation – misses</u>

Same as segmentation for hits but using S 99 marker.

<u>Average – hit</u>

<u>Average – miss</u>

<u>Baseline correction</u>

Re-corrected to the component onset for each ERP component.

<u>Peak detection</u>

*** Peak Detection ***

Automatic detection

Separate search for every channel

Local maxima was searched.

Appendix C

Visual CTET history tree

Immediate target processing

Change sampling rate

Conversion is based on spline interpolation.

New Sampling Rate [Hz]: 256

New Sampling Interval [µS]: 3906.25

Data was filtered before downsampling with 115.2Hz, 24dB/oct.

Mastoid & Eye formula (EXG3 = Below eye, EXG4 = above eye)

The following formulas were calculated:

Mastoid_average = (EXG1+EXG2)/2   Unit: µV

VEOG = EXG4-EXG3   Unit: µV

HEOG = EXG6-EXG5   Unit: µV

The remaining channels were kept.

The new channels are on top.

Mastoid reference

Selected channels to include into the new reference:

Mastoid_average

The implicit reference is included in the calculation of the new reference.

Channels to which the new reference applies to:

AF3 AF4 AF7 AF8 AFz C1 C2 C3 C4 C5

C6 CP1 CP2 CP3 CP4 CP5 CP6 CPz Cz F1

F2 F3 F4 F5 F6 F7 F8 FC1 FC2 FC3

FC4 FC5 FC6 FCz Fp1 Fp2 Fpz FT7 FT8 Fz

Iz O1 O2 Oz P1 P10 P2 P3 P4 P5

P6 P7 P8 P9 PO3 PO4 PO7 PO8 POz Pz

T7 T8 TP7 TP8

Remaining (non rereferenced) channels are kept.

Name of the new reference channel: Avg

Filters

Zero phase shift Butterworth filters.

Global filter settings:

Low cutoff: 0.5305164 Hz, time constant 0.3, order 2

High cutoff: 40 Hz, order 2

Notch filter: 50 Hz

Segmentation

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 72

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: -3200.00 ms, End: 3000.00 ms, Length: 6200.00 ms

Allow overlapped segments? Yes

Skip bad intervals? No

Data was not stored but will be calculated on demand.

*** Data node specific information ***

Number of segments: 203

Notch filter

Frequency	Bandwidth	Order
10.00000	2.00000	2

The following channels have been selected for filtering:

AF3	AF4	AF7	AF8
AFz	C1	C2	C3
C4	C5	C6	CP1
CP2	CP3	CP4	CP5
CP6	CPz	Cz	EXG1
EXG2	EXG3	EXG4	EXG5
EXG6	EXG7	EXG8	F1

F2 F3 F4 F5

F6 F7 F8 FC1

FC2 FC3 FC4 FC5

FC6 FCz Fp1 Fp2

Fpz FT7 FT8 Fz

HEOG Iz Mastoid_average O1

O2 Oz P1 P10

P2 P3 P4 P5

P6 P7 P8 P9

PO3 PO4 PO7 PO8

POz Pz Status T7

T8 TP7 TP8 VEOG

<u>Baseline correction</u>

Begin: 560 [ms]

End: 640 [ms]

<u>Artifact rejection</u>

Used Channels: 64

AF3 AF4 AF7 AF8 AFz C1 C2 C3 C4 C5 C6 CP1 CP2

CP3 CP4 CP5 CP6 CPz Cz F1 F2 F3 F4 F5 F6

F7 F8 FC1 FC2 FC3 FC4 FC5 FC6 FCz Fp1 Fp2 Fpz

FT7	FT8	Fz	Iz	O1	O2	Oz	P1	P10	P2	P3	P4
P5	P6	P7	P8	P9	PO3	PO4	PO7	PO8	POz	Pz	T7
T8	TP7	TP8									

Check Gradient:

Maximal allowed voltage step: 50 µV/ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Difference (Max-Min):

Maximal allowed difference of values in intervals: 200 µV

Interval Length: 200 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Amplitude:

Minimal allowed amplitude: -200 µV

Maximal allowed amplitude: 200 µV

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Low Activity:

Lowest allowed activity in intervals: 0.5 µV

Interval Length: 100 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

*** Data node specific information ***

Ocular Correction ICA

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Horizontal activity channel: HEOG.

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Data used for ICA: Whole data.

Number of ICA steps: 512.

Convergence bound: 1E-07.

Bound number of considered blinks at 60.

ICA algorithm used: Infomax Restricted.

Channels enabled for ICA:

Mastoid_average VEOG HEOG Fp1 AF7

AF3 F1 F3 F5 F7

FT7 FC5 FC3 FC1 C1

C3 C5 T7 TP7 CP5

CP3 CP1 P1 P3 P5

P7 P9 PO7 PO3 O1

Iz Oz POz Pz CPz

Fpz Fp2 AF8 AF4 AFz

Fz F2 F4 F6 F8

FT8 FC6 FC4 FC2 FCz

Cz C2 C4 C6 T8

TP8 CP6 CP4 CP2 P2

P4 P6 P8 P10 PO8

PO4 O2 EXG1 EXG2 EXG3

EXG4 EXG5 EXG6 EXG7 EXG8

Status

Target blink detection

*** Artifact Rejection - Automatic Inspection ***

Used Channels: 1

VEOG

Check Gradient:

Maximal allowed voltage step: 200 µV/ms

Mark as Bad: Before Event: 1000 ms After Event: 200 ms

Check only Intervals in Segments:

Segment No.: IntervalStart [ms]: IntervalLength [ms]:

0 - 203 -3200 6199

8Hz Low Pass filter

*** IIR Filters ***

Zero phase shift Butterworth filters.

Global filter settings:

Low Cutoff: ---

High cutoff: 8 Hz, order 2

Notch filter: ---

Import markers

Segmentation – hits

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 98

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: -100.00 ms, End: 2000.00 ms, Length: 2100.00 ms

Allow overlapped segments? No

Skip bad intervals? Yes

Data was not stored but will be calculated on demand.

*** Data node specific information ***

Number of segments: 36 (This is only for participant 1)

<u>Segmentation – misses</u>

Same as above for Segmentation – hits (but use S 99 instead of S 98).

<u>Average – hits</u>

<u>Average – misses</u>

<u>Peak detection</u>

*** Peak Detection ***

Automatic detection

Separate search for every channel

Local maxima was searched.

Short term pre-target processing

Same pre-processing steps as the Immediate target processing up until the first Segmentation.

Segmentation

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 72

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: -3280.00 ms, End: 3000.00 ms, Length: 6280.00 ms

Allow overlapped segments? Yes

Skip bad intervals? No

Data was not stored but will be calculated on demand.

Notch filter

Frequency	Bandwidth	Order
10.00000	2.00000	2

The following channels have been selected for filtering:

AF3	AF4	AF7	AF8
AFz	C1	C2	C3

C4	C5	C6	CP1
CP2	CP3	CP4	CP5
CP6	CPz	Cz	EXG1
EXG2	EXG3	EXG4	EXG5
EXG6	EXG7	EXG8	F1
F2	F3	F4	F5
F6	F7	F8	FC1
FC2	FC3	FC4	FC5
FC6	FCz	Fp1	Fp2
Fpz	FT7	FT8	Fz
HEOG	Iz	Mastoid_average	O1
O2	Oz	P1	P10
P2	P3	P4	P5
P6	P7	P8	P9
PO3	PO4	PO7	PO8
POz	Pz	Status	T7
T8	TP7	TP8	VEOG

<u>Segmentation (target – 1, target – 2, target – 3, target – 4)</u>

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 72

Advanced Boolean Expression:

Baseline correction

*** Baseline Correction Transformation ***

Begin: -78.125 [ms]

End: 0 [ms]

Artifact rejection

Used Channels: 64

AF3	AF4	AF7	AF8	AFz	C1	C2	C3	C4	C5	C6	CP1	CP2
	CP3	CP4	CP5	CP6	CPz	Cz	F1	F2	F3	F4	F5	F6
	F7	F8	FC1	FC2	FC3	FC4	FC5	FC6	FCz	Fp1	Fp2	Fpz
	FT7	FT8	Fz	Iz	O1	O2	Oz	P1	P10	P2	P3	P4
	P5	P6	P7	P8	P9	PO3	PO4	PO7	PO8	POz	Pz	T7
	T8	TP7	TP8									

Check Gradient:

Maximal allowed voltage step: 50 µV/ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Difference (Max-Min):

Maximal allowed difference of values in intervals: 200 µV

Interval Length: 200 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Amplitude:

Minimal allowed amplitude: -200 µV

Maximal allowed amplitude: 200 µV

Mark as Bad: Before Event: 200 ms After Event: 200 ms

Check Low Activity:

Lowest allowed activity in intervals: 0.5 µV

Interval Length: 100 ms

Mark as Bad: Before Event: 200 ms After Event: 200 ms

*** Data node specific information ***

<u>Ocular Correction ICA</u>

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Horizontal activity channel: HEOG.

Components relevant for vertical activity based on the relative variance in the respective channel.

Percentage of variance to delete: 30 %.

Data used for ICA: Whole data.

Number of ICA steps: 512.

Convergence bound: 1E-07.

Bound number of considered blinks at 60.

ICA algorithm used: Infomax Restricted.

Channels enabled for ICA:

Mastoid_average VEOG HEOG Fp1 AF7

AF3 F1 F3 F5 F7

FT7 FC5 FC3 FC1 C1

C3 C5 T7 TP7 CP5

CP3 CP1 P1 P3 P5

P7 P9 PO7 PO3 O1

Iz Oz POz Pz CPz

Fpz Fp2 AF8 AF4 AFz

Fz F2 F4 F6 F8

FT8 FC6 FC4 FC2 FCz

Cz C2 C4 C6 T8

TP8 CP6 CP4 CP2 P2

P4 P6 P8 P10 PO8

PO4 O2 EXG1 EXG2 EXG3

EXG4 EXG5 EXG6 EXG7 EXG8

Status

Target blink detection

*** Artifact Rejection - Automatic Inspection ***

Used Channels: 1

VEOG

Check Gradient:

Maximal allowed voltage step: 200 µV/ms

Mark as Bad: Before Event: 1000 ms   After Event: 200 ms

Check only Intervals in Segments:

Segment No.: IntervalStart [ms]: IntervalLength [ms]:

0 - 203   -3200   6199

<u>8Hz Low Pass filter</u>

*** IIR Filters ***

Zero phase shift Butterworth filters.

Global filter settings:

Low Cutoff: ---

High cutoff: 8 Hz, order 2

Notch filter: ---

<u>Import markers</u>

<u>Segmentation – hits</u>

Segmentation relative to reference marker positions

Reference markers:

Stimulus S 98

Advanced Boolean Expression:

Segment size and position relative to reference markers:

Start: 0.00 ms, End: 600.00 ms, Length: 600.00 ms

Allow overlapped segments? No

Skip bad intervals? Yes

Data was not stored but will be calculated on demand.

Segmentation – misses

Same as segmentation for hits but using S 99 marker.

Average – hit

Average – miss

Baseline correction

Re-corrected to the component onset for each ERP component.

Peak detection

*** Peak Detection ***

Automatic detection

Separate search for every channel

Local maxima was searched.

Appendix D

Subject selection

Participants with a hit to false alarm (H/FA) rate if below 3 were excluded from EEG analysis. The following table shows the task order and the H/FA rates across the whole sample.

Table 1.

Task order and H/FA rates for both tasks across the entire sample.

Pts	**Task completed 1st**	**Visual H/FA**	**Auditory H/FA**
1	Auditory	5.353	55.667
2	Visual	4.810	0.432
3	Auditory	0.273	0.350
4	Visual	24.833	27.333
5	Auditory	0.179	0.170
6	Visual	0.284	2.541
7	Visual	2.419	0.581
8	Auditory	3.833	16.000
9	Auditory	0.219	0.675
10	Auditory	0.352	0.267
11	Auditory	38.000	0.667
12	Auditory	0.311	0.295

13	Auditory	11.571	21.250
14	Auditory	10.375	25.167
15	Visual	0.464	0.614
16	Visual	3.563	198.000
17	Visual	4.382	6.087
18	Visual	171.000	183.000
19	Visual	6.952	35.750
20	Visual	41.500	5.643
21	Auditory	1.089	6.722
22	Visual	Not complete	2.919
23	Visual	7.000	0.903
24	Auditory	0.287	0.322
25	Auditory	1.720	0.764
26	Auditory	0.885	1.973
27	Visual	1.691	0.269
28	Auditory	3.806	130.000
29	Visual	38.500	149.000