Orienting of willed temporal attention: an EEG study

Maciej Malinowski

M00547197

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Middlesex University, London

School of Science and Technology

Supervisors Dr Alexander Jones and Dr Jonathan Silas

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Preface and Impact of COVD-19

This study was preregistered at the Open Science Foundation website before the data collection started (registration documents can be found here: https://osf.io/z2r69/ or in Appendix A). The OSF is a free web application. It aims to increase openness, integrity, and reproducibility of scientific research. On that website, full details regarding the study were provided. Specifically, a detailed design plan, sample size rationale, pre-processing and statistical analyses, as well as data exclusion criteria, were described. Furthermore, all hypotheses were listed, and the experiment file was uploaded. Therefore, all details regarding my study were planned before the data collection started. However, due to the pandemic, I was not able to follow all of the steps described in that document. Specifically, I could not collect enough data. Thus, this was an underpowered study which affected the way I could interpret the results. All the interpretation in the discussion were, therefore, speculative. Furthermore, I had designed the experiment fully in the E-Prime software which took me 4 months to finalise and I had collected 13 participants before it became impossible to collect data. I started collecting data in the mid-March as I wanted to finish the OSF registration which would mean that my research would be conducted to a high academic standard. Therefore, because the substantial amount of work had been done, I decided to follow the original plan specified in the OSF and to complete this thesis as a proof of concept. Following the original plan would be a better learning experience as I was able to conduct all the analyses specified in the OSF. Also, redesigning my experiment and completing a new project would not be possible.

Abstract

Temporal attention enables people to select relevant stimuli across time allowing for prioritisation of information. In most studies on temporal orienting external cues have been used to direct participants' attention. However, in everyday life, we also make internal choices, without external cues, of when to orient our attention. Recent studies in visual-spatial attention developed a paradigm aiming to explore how voluntary attention is initiated and controlled when no direct instructions are used. This paradigm includes a new type of trial in which a participant is asked to choose where to orient their attention (willed attention) in contrast to being instructed where to orient their attention (instructed attention). The current study draws on this distinction and it aims to explore whether and how willed temporal attention affects behaviour and whether it is different from instructed temporal attention by looking at both behavioural data as well as EEG. To explore that question the temporal cueing task was used in which a cue instructed a participant to anticipate either short (800 ms) or a long (2000 ms) interval between cue and target presentation times. Alternatively, a cue instructed a participant to decide for themselves to expect the target after one of these two intervals. The experiment demonstrated no significant differences in RTs and EEG recordings. However, a difference between two attention types in the CNV recorded in the time interval directly preceding the target in the short cue-target interval showed a medium effect size. Furthermore, a comparison of the CNV recorded in the willed and instructed attention in the post cue time interval demonstrated medium effect size with posterior scalp distribution. It was only recorded in the short cue-target interval. There, also, was a lateralised activity in the N1 time range in the instructed attention condition. Finally, a small decrease in the power of the theta activity was observed in the willed attention condition in the long cue-target interval at the Fz electrode. These differences could potentially become significant with more power. To the author's

knowledge, this is the first study on electrophysiological correlates of willed temporal attention, and it demonstrates the feasibility of the paradigm used.

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Contents

1. Introduction

1.1 Timing

Perception of time underlies perceptual, motor, and cognitive activities allowing an individual to anticipate changes in the environment to adjust their behaviour. Thus, time perception is a basic aspect of people's mental functioning (Mento, Tarantino, Sarlo, & Bisiacchi, 2013). This ability is shared across different species suggesting that the processing of time does not necessitate complex neuroanatomical mechanism (Anderson & Sheinberg, 2008; Coull, Cheng, & Meck, 2011; de Hemptinne, Nozaradan, Duvivier, Lefevre, & Missal, 2007; Jaramillo & Zador, 2011). People can infer environmental regularity and, subsequently, develop a temporal expectation implicitly (implicit timing; Mento, 2013). A temporal expectation reflects a neural system response related to the timing of an event. It should not be confused with volition or conscious deliberation (Nobre & Van Ede, 2018). This temporal expectation will fade if an environmental regularity does not contain vital information suggesting that the timing mechanism has automatic but variable output (Macar & Vidal, 2009). Implicit timing refers to a situation where a person uses temporal information without explicitly focusing on it, to achieve non-temporal task goals. For instance, when an individual estimates the appropriate time needed to cross a street before a car. In studies using implicit timing tasks, a temporal association is established between two stimuli. This temporal association influences someone's performance on a task. Time can also be perceived explicitly which refers to an overt estimation of a duration of an event. In studies using explicit timing tasks, participants typically state whether the duration of one stimulus or interstimulus interval (ISI) is longer or shorter in comparison to the length of another (Coull et al., 2011).

There is also evidence to suggests that different timing mechanisms are used for the processing of sub- and supra-second intervals (Buonomano, 2007; Meck, 2005; Rammsayer, 1999). Support for that suggestion comes from studies exploring the role of the various brain

regions in the processing of these time intervals (Fierro et al, 2007; Koch et al, 2007). Evolutionarily, processing of time within seconds range was vital for anticipating changes in the environment whereas sub-second time perception was vital for motor control and rapid organisation of cognitive processes increasing chances of survival (Meck, 2005). Furthermore, these intervals operate in the context of slower fluctuations such as circadian rhythms (Nobre & Rohenkohl, 2014).

1.2 Timing in the brain

The cerebellum was proposed to be engaged in the processing of the sub-second time intervals (Coull, et al., 2011). This suggestion was supported by the research using transcranial magnetic stimulation (TMS) as applying stimulation to the cerebellum resulted in the impairments in the processing of intervals only under a second (Fierro et al, 2007; Koch et al, 2007). Furthermore, the right prefrontal cortex was suggested to be engaged in the processing of supra-second time intervals. It was indicated by impairments in the processing of these intervals found in patients with lesions to this area as well as impairments induced by the TMS stimulation (Koch et al., 2007; Koch, Oliveri, Carlesimo, & Caltagirone, 2002).

fMRI research using healthy participants have repeatedly shown heightened activation of the dorsal striatum of the basal ganglia by timing performance (Coull & Nobre, 2008; Meck, Penney, & Pouthas, 2008). Coull, Vidal, Nazarian, and Macar (2004) used a paradigm where they parametrically varied attention to length (from 500 ms to 1600 ms) and/or colour (from reddish to blueish) of a stimulus so that participants could later compare it for duration or hue. They had five different conditions in which participants were asked to attend to time, to time more than colour, equally to both features, to colour more than time or to colour only. Their behavioural data showed that participants focused their attention appropriately across all conditions. Decreasing attentional focus on time was associated with progressive slowed reaction times (RTs) in time trials but speeded them in colour trials. The fMRI recoding

indicated that focusing attention on time was associated with the activation mainly in the supplementary motor area (SMA) as well as basal ganglia. These regions differed from a region activated by attention directed to colour, V4. These findings were extended by research where participants need to compare the duration of stimuli of different lengths which did not require a motor response. This research also indicated the engagement of basal ganglia and SMA in timing performance (Coull et al., 2011). There is also evidence to suggest that time induced basal ganglia activity was independent of the interval duration range, the motor response being timed, as well as the modality of a stimulus which might suggest that context-independent timer mechanism could be located in the dorsal striatum of the basal ganglia (Coull, et al., 2011). One of the well-cited models that describe such a centralised internal-clock responsible for time perception is the pacemaker-accumulator (Hartcher-O'Brien, Brighouse, & Levitan, 2016; Treisman, 1963). In this model, time is represented on the continuous parametric timescale. The sensory signal, for instance, a stimulus presentation causes the accumulator to start counting pulses emitted by an internal pacemaker. Later, the number of pulses counted is forwarded into the working memory. The appropriate response can be given based on that information (Hartcher-O'Brien et al., 2016; Treisman, 1963).

In contrast, other research suggests that time perception relies on the pattern of neural firings occurring within distinct specialised areas (Mauk & Buonomano, 2004). Therefore, it does not depend on centralised timer mechanism but instead, it relies on a much more distributed network. The processing of timing of an auditory stimulus would engage the auditory cortex. Similarly, processing of the timing of a visual stimulus would involve visual cortex (Coull et al., 2011). This suggestion seems to be supported by the observation that there are no disorders that are reflected by temporal deficits, in a similar way to conditions such as neglect which is reflected by spatial deficits. Research suggesting the dispersed way of timing processing focused on short sub-second durations requiring less attentional and mnemonic

resources (Coull et al., 2011). It is then possible that centralised timing mechanism, such as a pacemaker-accumulator could be necessary for processing of longer durations requiring more attentional and mnemonic resources. The exact description of the networks and mechanisms facilitating perception of time is still lacking (Nobre, & Rohenkohl, 2014). Some of the structures involved in the time perception such as the cerebellum, basal ganglia, and SMA, have also been associated with motor preparation. It suggests that processes related to these cognitive functions potentially share brain networks. This suggestion seems to be supported by people's daily experiences as accurate timing is important for motor preparation and precise limb-movements (Mento et al., 2013). Furthermore, the timing system when it is necessary is sensitive to attentional control (Macar & Vidal, 2009).

1.3 Temporal and spatial attention

Attention plays a fundamental role in human cognition and behaviour allowing people to cope with the continuous and complex stream of new information present in the environment (Rueda, Pozuelos & Cómbita, 2015). In the previous research, models of attention included control, selection, and alerting aspects. The control aspect of attention reflects voluntary goal-directed behaviour. Processes involved in attentional control include inhibition of the automatic course of behaviour and conflict resolution. The selection aspect refers to processes that allow an individual to choose relevant information, which can be either internal or external stimuli, for processing. Alerting aspect of attention reflects the maintaining of an optimal level of activation necessary for selection and control function to be utilised effectively (Petersen & Posner, 2012; Rueda, et al., 2015).

The abovementioned aspects of attention can be further subdivided. Selection can be divided depending on whether it is driven by external stimuli such as an abrupt change in the environment that attracts attention, for example, passer-by crossing a street (exogenous or bottom-up attention) or by internal stimuli such as a voluntary intention, for example, attending

to traffic lights to adjust a driving behaviour (endogenous or top-down attention). Similarly, alerting can be divided along the same axis as it can be changed according to internal motivation or a change in the environment. The processes that are related to attentional control have typically been treated as endogenous processes (Rueda et al., 2015). Furthermore, events in the environment, across different modalities, are constrained by their spatial location. Also, the environment unfolds dynamically, and events temporal structures carry predictions important for an individual's behaviour (Nobre & Van Ede, 2018). Therefore, attention relies on the decoding of this spatiotemporal context. Attention, thus, is a multifaceted construct comprising various cognitive brain mechanisms that enable people to select relevant stimuli, across time (temporal attention) and space (spatial attention), while at the same time ignoring irrelevant ones. By this definition, attention is at the centre of perception and performance (Rueda, et al., 2015).

1.4 Temporal structure

Temporal attention has received less research focus than spatial attention. However, the influence of different temporal structures on an individual's behaviour has not always been overlooked. Temporal structures are underlying time relations that connect different events in the environment. They can be sensed and utilised by an individual to optimise their behaviour (Nobre & Van Ede, 2018). Wundt (1904) indicated that providing people with information pertaining to the target onset time is associated with faster RTs. In his experiment, participants needed to release a key when a ball hit a metal plate. Wundt (1904) recorded faster RTs when participants could watch the machine dropping the ball. Woodrow (1914) noticed people's RTs were faster when time interval dividing two stimuli were predictable. These early studies started to explore how temporal structures of events influences behaviour and they opened a question of underlying neural mechanisms. However, these studies were not followed by later research leaving open the exact explanation of neural correlates of temporal attention and its

relations with spatial attention. Recently, more research has begun to explore, using different paradigms, how various temporal structures can shape perception and optimise behaviour (Nobre & Van Ede, 2018). Here, three types of structures will be considered: rhythms, hazard function, and associations.

1.4.1 Rhythms

Some events and activities in the environment have a rhythmic structure: footstep, musical beats, and speech. Rhythmic tasks have been used to explore rhythms influence on perception and performance. For instance, Jones, Moynihan, MacKenzie, and Puente (2002) used pitch-judgment tasks in their three experiments. Their participants were presented with standard and comparison sounds. They were asked to decide whether the comparison sound had the same, higher, or lower tone in contrast to the standard sound. These stimuli were separated by another rhythmically timed sounds. Onset time of the comparison stimulus was variable relative to the preceding rhythm. The authors demonstrated that the participants were most accurate when the comparison sound was presented synchronously with the preceding rhythm. The participants were the least accurate when tones were presented at unexpected times. These findings are in line with the Dynamic Attending Theory which states that rhythms create windows of increased attentional focus that enhances sensory processing. Thus, the processing of stimuli is optimal when they are presented in a rhythmic context (Jones & Ward, 2019).

Recently, Jones and Ward (2019) extended these findings in their study where they presented their participants with a stream of checkerboards and images of daily objects. The ISI separating these images and checkerboards had either constant duration, therefore, creating a rhythm or variable duration creating an arrhythmic presentation of stimuli. After, image presentation participants took part in the recognition task. This study demonstrated that presenting participants with images in rhythmic context is associated with improved

performance on the recognition task in contrast to images presented in an arhythmic context suggesting that rhythms in the environment can also influence other cognitive functions beyond attention (Jones & Ward, 2019).

1.4.2 Hazard function

The hazard function is another temporal structure present in the environment that influences someone's behaviour. It is a likelihood of an event occurring at the specific time given that it has not occurred yet. Therefore, it increases with the flow of time (Luce, 1986). For example, a probability of a streetlight becoming green increases with time. Therefore, a driver preparation also increases with time as a function of this information facilitating faster response. Most temporal attention research has hazard function embedded within their paradigms. The hazard function might drive what is known as the foreperiod effect which is a modulation of behavioural response driven by an aspect of the time interval used in the study. The hazard function is a general phenomenon whereas the foreperiod effect is a phenomenon specific to the effect in an experimental task (Nobre & Rohenkohl, 2014). Often, studies that investigate the influence of hazard function on performance manipulate the temporal expectation by changing the probability of target onset times that follows the warning signal. The behavioural results demonstrate that the RTs are decreasing with higher expectation indicating that they are modulated by hazard function (Cravo, Rohenkohl, Wyart, & Nobre, 2011; Nobre, Correa, & Coull, 2007). It is unclear how many different temporal characteristics of an event can induce temporal expectations related to hazard function. However, some of them are length, regularity, sequence, and cued probability (Nobre & Rohenkohl, 2014). Interestingly, the effect of hazard function is not observed in patients with damage to the right prefrontal cortex (Triviño, Correa, Arnedo, & Lupiáñez, 2010). It was suggested that it is associated with the monitoring function of the right prefrontal cortex which uses sensory

feedback to update temporal expectations (Coull et al., 2011). These findings provide further support for the role of prefrontal cortex in the processing of time.

The influence of hazard function on behaviour was found not only in people but also in other species. For example, de Hemptinne, Nozaradan, Duvivier, Lefevre, and Missal (2007) used anticipatory pursuit paradigm to study the effect of predictability of future events on the behaviour of rhesus monkeys in their two experiments. In the anticipatory pursuit paradigm, smooth movements of eyes, initiated in expectation of a moving target presentation, are recorded. Each trial in these experiments started with the presentation of a steady stimulus (a dot). After 500 ms this stimulus disappeared from the screen which marked the beginning of the ISI. In the first experiment, the ISI could be either 400 ms or 1200 ms long whereas in the second experiment the ISI was a random time interval drawn from bimodal density function. When ISI ended the same stimulus was presented and it moved from one side of the screen to the other. The authors analysed the velocity and latency of monkeys smooth-pursuit eye movements. It was assumed that if the monkeys estimate the hazard function to optimise their anticipatory response these behavioural indices would be affected. In their first experiment, they recorded the first increase in the velocity of the eye movements around 200 ms prior to the second stimulus presentation. If the second stimulus was not presented after the short delay the eye velocity decreased. Considering that the target was not presented after the short delay it was certain that stimulus would be presented after the long delay. It was reflected in the behavioural response as a second increase in the eye velocity was recorded prior to the expected end of the long delay. The increase in eye velocity stopped with the onset of visual pursuit. Furthermore, increasing the target onset time uncertainty, in their second experiment, was associated with an increased width of the latency distribution of the pursuit response. The authors interpreted these results as evidence that monkeys use changes in the hazard function to guide their anticipatory response.

1.4.3 Associations

Another temporal structure present in the environment is a temporal association which is a specific time relation connecting successive events (Nobre & van Ede, 2018). It can be reflected in a situation where traffic starts moving a moment after the light turns green. The paradigm used in research on temporal associations is typically a variation of the cueing paradigm introduced by Posner (1980). In this paradigm, a cue guides a participant to focus their attention on a specific location on the screen where a response-relevant stimulus may appear. The process of directing attention towards a specific location is called orienting of attention. In experiments exploring the effects of temporal associations, symbolic cues guide a participant to orient their attention to different points in time instead of space when a target may appear (Nobre & van Ede, 2018). This paradigm builds on the previous research studying the influence of the above described foreperiod effect on RTs (see Niemi & Näätänen, 1981 for review).

Differences in RTs as well as differences in neural recordings observed between valid and invalid trials, in the experiments using this paradigm, are considered as an indication of attentional orienting. On valid trials, a cue used to guide someone's attention contains correct information with regards to a target stimulus onset time. For example, a cue instructs a participant to attend to the end of a specific time interval and a target is presented at that moment. Target on those trials can also be called cued stimuli. In contrast, on invalid trials, an attention-guiding cue contains incorrect information pertaining to the target stimulus onset time. The example of an invalid trial is when a cue instructs a participant to attend to the end of a specific time interval, but a target is presented at the end of an alternative interval. Target on those trials can also be called uncued stimuli. Posner (1980) demonstrated the behavioural effects of orienting of attention to spatial locations. Specifically, RTs were faster when people were presented with valid information, in contrast to invalid information.

1.5 Brain areas of temporal and spatial attention

Corbetta and Shulman (2002) suggested that two distinct attentional networks, both involving different regions within the parietal cortex, govern different functions of attentional orienting. The first one called dorsal attentional network (DAN) is located bilaterally and includes areas in the intraparietal sulcus (IPS) and frontal eye fields (FEF). The first research indicating the role of DAN in the attention orienting was conducted for spatial attention in the visual modality (Caspers, Amunts, & Zilles, 2012). The DAN network was suggested to underlie goal-directed endogenous attention. The activation of this network that follows attention-guiding cue is a highly reproducible finding (Caspers et al, 2012, Hopfinger, Buonocore, & Mangun, 2000; Liu, Bengson, Huang, Mangun, & Ding, 2016; Wang, Rajagovindan, Han, & Ding, 2016; Wen, Yao, Liu, & Ding, 2012).

The second network is called the ventral attention network (VAN) and it is located mainly in the right hemisphere comprising temporoparietal junction (TPJ) and the ventral frontal cortex. This network is involved in the detection of the unattended but behaviourally relevant stimulus and subsequent reorientation of attention towards that stimulus (Corbetta & Shulman 2002). The suggestion that this network is lateralised to the right hemisphere is supported by studies indicating that attention disengagement, necessary for reorienting process, deficits are typically greater in people with the right than left parietal damage. Similarly, the first research supporting the function of this network was conducted for spatial attention in the visual modality (Caspers et al., 2012). However, later attention research recorded a similar pattern of activation, in these two networks when stimuli were defined by different criteria such as shape or colour as well as other than visual modality such as auditory or tactile (Macaluso, 2010). Chica, Bartolomeo, and Valero-Cabré (2011) applied TMS to the right IPS and TPJ in order to affect the allocation of attention following a spatial cue. In the exogenous condition, a cue was non-informative about the target location. In other words, 50% of the trials were valid

and 50% of trials were invalid. In the endogenous cueing task 67% of the cues were valid and the remaining 33% invalid. They found that applying TMS stimulation to IPS affected both exogenous and endogenous attention. However, TMS to the TPJ affected only exogenous attention. Furthermore, Corbetta and Shulman (2011) indicated in their meta-analysis that both networks are activated in concert during attention reorienting to different spatial location. These results suggest that these two networks are not functionally distinct but instead they are interacting with each other and that different functions of attention should not be associated only with a single network.

Coull and Nobre (1998), to differentiate above described neural structures of spatial attention orienting from temporal attention orienting, conducted a study in which they adapted the Posner-style cueing task. They had four types of cues that predicted target spatial location as well as target onset time, target location only, target onset time only, and neutral cues that did not contain any information. In this experiment, the authors manipulated participants' expectations of where or when target stimuli would appear. Target onset times were 300 ms and 1500 ms relative to the cue offset time and participants' task was to detect the peripheral target stimuli. Coull and Nobre (1998) demonstrated a partial overlap between brain regions engaged in the orienting of both spatial and temporal attention. The left IPS and the left inferior premotor cortex were associated with temporal attention whereas right IPS activation was associated with spatial attention. Furthermore, the combined spatial-temporal expectation was reflected in the activation of predominantly parietal regions. The parietal cortex was activated the most when participants oriented their attention across both dimensions in contrast to space and time alone. The suggestion that neural structures of spatial and temporal attention overlap is further supported by observations that patients with neglect syndrome have impaired ability to use temporal information to guide their attention. Neglect syndrome is defined as an impairment in the orienting of spatial attention (Husain, Shapiro, Martin, & Kennard, 1997;

Roberts, Lau, Chechlacz, & Humphreys, 2012). Furthermore, other studies have also shown the activation of IPS, inferior premotor cortex as well as the anterior inferior parietal lobule in the control of temporal orienting (Cotti, Rohenkohl, Stokes, Nobre, & Coull, 2011; Coull, Davranche, Nazarian, & Vidal, 2013). Nobre and Rohenkohl (2014) suggested that this network is different from the network involved in spatial orienting. It is lateralised to the left hemisphere and it has a more inferior location which suggests that it includes inferior parietal and frontal areas associated with a motor response control and preparation.

1.6 EEG research on temporal attention

The aforementioned neuroimaging techniques have helped researchers to describe the neural networks underlying the orienting of temporal attention. However, these techniques provide little explanation of the temporal dynamics of cortical activation involved in that process. Electroencephalography (EEG) has been used to investigate this. EEG is a non-invasive technique that records voltage fluctuations in response to a specific sensory or motor events (Luck & Kappenman, 2011). Using electrodes placed on the scalp, EEG records summed electrical activity from large populations of neurons in the cortex generated in the extracellular fluid as neurons communicate with each other. Furthermore, the simultaneously active neurons must have approximately the same orientation for the potentials to summate (Woodman, 2010). As a result, most of the events occurring in the brain cannot be measured with this technique and EEG amplitude mainly reflects the amount of synchronisation in the cortical areas (von Stein & Sarnthein, 2000). EEG records diffused electrical activity providing a poor spatial resolution, however, it records moment-by-moment continuous activity. Therefore, it provides a high temporal resolution and is thus very well suited to investigate the underlying processes involved in temporal attention.

The analysis of the EEG data can be done in the time or frequency domain. The time-domain analysis is conducted by extracting, pre-processing, and averaging segments of EEG

data around a stimulus of interested that is marked by an event code called a trigger or marker. EEG also contains an activity that is not driven by a stimulus which cancels each other out during averaging as a result of the phase variability relative to an event. Phase describes the angle or change of the waveform relative to the fixed position. Therefore, the averaging process leaves a waveform, called an Event-Related Potential (ERP), consisting only of stimulus-driven activity that is phase-locked and time-locked (Luck & Kappenman, 2011). Using ERPs in research has become common after Walter, Cooper, Aldridge, McCallum, and Winter (1964) suggested that the cognitive activity related to an experimental task can be recorded with this technique. They found that the negative voltage deflection developed before the presentation time of the stimulus to which participants were asked to respond. Letters 'P' and 'N' are conventionally used to name separate components of the ERP. These letters are used to indicate positive (P) and negative (N) peaks and they are typically followed by a number which may indicate a peak's position within the waveform (e.g. P1 is the first major positive peak). Alternatively, the number may indicate the latency of the peak in millisecond (e.g. P300 can describe positive peak appearing approximately at 300 ms post-stimulus; Luck & Kappenman, 2011). Recording and interpreting ERPs have helped researchers to better characterise different cognitive mechanisms involved in the performance of a task.

These task-related cognitive processes, reflected in the stimulus-locked ERP waveform, are preceded by the propagation of sensory information through sensory organs and sensory pathways in the brain. Analysis of the sensory components can be useful in determining the efficacy of a stimulus used in the research. Furthermore, analysis of sensory components is of interest in the research focused on people with psychiatric and neurological problems. It can be used to investigate if a disorder influences sensory input to patient cognitive processing (Pratt, 2012). Furthermore, it is now recognised that influencing of brain regions responsible for sensory analysis, such as visual areas, during the stimulus-induced expectation emerges

from areas in the frontoparietal cortex (see section 1.5 Brain areas of temporal and spatial attention for description). These networks provide "bias signals" that can increase or suppress sensory activity in the extrastriate cortex depending on the importance of the stimuli determining which information will be processed or suppressed (Vossel, Geng, & Fink, 2014). Therefore, analysis of potentials reflecting the perceptual processing can be a useful first step in explaining the various cognitive processes reflected in an ERP.

In visual attention research, the potentials reflecting the perceptual processing of stimuli are P1 and N1 which are generated in extrastriate cortex in the occipital lobe. The P1 wave is typically recorded in the time range 60 – 100 ms post-stimulus whereas N1 in the time range 100 – 200 ms post-stimulus (Woodman, 2010). Several different subcomponents have been proposed to contribute to the N1. For example, a component generated in the auditory cortex, a component generated in the association cortex, and a component generated in the motor and premotor cortices (for review see Näätänen & Picton, 1987). The majority of research has focused on how we orient attention in space, and it demonstrated that stimuli displayed at the attended location are associated with larger P1 and N1 than stimuli presented at the unattended location with minimal change of these ERPs latencies. These changes were named the P1 and N1 attention effect (Luck, 1995; Mangun & Hillyard, 1987; Vogel & Luck, 2000). Moreover, this enhancement of the P1 and N1 amplitude was correlated with decreased RTs to a stimulus presented at the attended location. It suggests that changes in these ERPs amplitude are reflective of the sensory information being used for perceptual judgments (Hillyard & Anllo-Vento, 1998).

Changes in the P1 amplitude can be observed without changes in the N1 amplitude and vice versa indicating that these two early potentials reflect different mechanisms of attention (Vogel & Luck, 2000; Woodman, 2010). Vogel and Luck, (2000) conducted a research using

paradigm designed to measure electrophysiological correlates of discriminative processing. In this experiment, the stimuli were five-letter arrays presented centrally for 100 ms followed by variable ISI. This study consisted of two tasks, simple-RT task and choice-RT task. In the former, the participants were instructed to press a button at the onset of each letter array. In the latter, the participants were asked to look for a specific target letter or a target colour in each array. The results indicated that N1 in the choice-RT task was larger compared with N1 in the simple-RT task. This effect was equally large for different difficulty levels of the discrimination task. These results indicate that N1 component apart from being involved in the perceptual processing is also involved in stimuli discrimination.

Furthermore, the oscillatory activity comprising various frequency bands can be recorded with EEG and have also been modulated by attention. The frequency bands observed in human EEG research are conventionally divided into five different frequency ranges. These ranges are delta (<4 Hz), theta (4-8 Hz), alpha (8-13 Hz) beta (13-30 Hz), and gamma (>30 Hz). Each frequency band can be further sub-divided, e.g. low alpha, high beta (Luck, 2014). The margins of these frequency bands can be defined slightly differently by different researchers (Newson & Thiagarajan, 2019). The activity from one peak to another peak is defined as one cycle of the oscillation. If a cycle lasts for 100 ms, then there are 10 cycles in the second. Thus, this oscillation has a frequency of 10 Hz which is within alpha range (Luck, 2014). Both oscillations and ERPs change as a function of involvement in a task. Time-frequency analysis extracts the amplitude at a specific frequency bandwidth at a specific time point prior to the averaging process. That allows researchers to extract non-phase locked information eliminated in the ERP averaging process. The EEG analysis can be cue-locked which looks at the neural activity in the time after a cue but before the presentation of the target stimuli. Alternatively, the EEG analysis can be target-locked which focuses on brain activity following a target onset time (Cohen, 2014).

The most widely reported frequency band associated with attention is alpha. During attention orienting to spatial location, the contralateral hemisphere demonstrates a decrease in alpha activity whereas the ipsilateral hemisphere shows an increase in alpha amplitude. This process is called alpha lateralisation and it is an index of spatial attention orienting (Jensen & Mazaheri, 2010). Alpha lateralisation is thought to reflect the state of sensory readiness resulting in the enhancement of the processing of sensory information (Rajan et al., 2019). Although there is some evidence of alpha-band during anticipation of task-relevant stimuli in research inducing temporal expectation using rhythms, hazards, and anticipations (Wöstmann, Maess, & Obleser, 2020), the exact contribution of alpha oscillation to temporal expectation remains largely unexplored.

1.7 Perceptual modulations of temporal attention

Miniussi, Wilding, Coull, and Nobre (1999) using a variation of Coull and Nobre (1998) paradigm conducted the first ERP experiment on the orienting of temporal attention. In their experiment, two symbolic cues (narrow and wide cross) indicated the likely time interval after which a target would be presented. Only one of these cues was flashed on the screen for 100 ms on a trial. The participants' task was to respond to the target which was the brightening of the circle surrounding the cue for 100 ms. The time interval after which a target could be presented was either short (600 ms) or long (1400 ms). These two possible time intervals were presented in a randomized order and one cue corresponded only to a single time interval. Catch trials where the target was not presented after a cue was displayed with a probability of 0.10. Invalid trials where the target was presented at the unexpected interval (e.g. cue indicated the short interval, but the target appeared at the long interval) were also displayed with the probability of 0.10. Remaining trials were valid (e.g. cue indicated the short interval, and the target appeared at the short interval). An important aspect of their design was that all stimuli were displayed centrally, therefore, no spatial information was present. In the experiment, the

target presented on valid and invalid trials were response relevant. Thus, the participants were required to respond to the target regardless of whether it was presented at the expected interval or unexpected interval.

The results indicated that presenting the target at expected intervals was associated with a decrease in RTs compared to a target presented at unexpected intervals. However, this effect was only visible at a short interval. There were no differences in RTs between expected and unexpected targets at the long interval. Furthermore, the authors found attentional modulations in late ERP components related to response preparation and decision. For example, they found the changes in the P300 latency and amplitude. Specifically, it peaked earlier, and it had larger amplitude for cued targets compared with uncued targets. Modulation of P300 latency is commonly not observed in the spatial attention research. Miniussi et al. (1999) also found that the N2 component, reflecting post-perceptual processing of stimuli, was affected by temporal attention. Uncued targets were associated with enhanced N2 over occipital sites. Miniussi et al. (1999) interpreted N2 as reflecting the neural processing of the violation of the expected stimuli association.

In their experiment, temporal attention was not associated with differences in amplitude of the early perceptual potentials P1 and N1 which are typically found to be modulated by spatial attention. However, Minisussi et al. (1999) did not draw strong conclusions from their results. In their study, stimuli were presented centrally, therefore, they were already visually optimised. Thus, potentially, the participants did not need to engage in a target more. Consequently, the paradigm used could not have enough sensitivity to record perceptual modulations. This led some researchers to suggest that using stimuli requiring more detailed perceptual analysis could result in the modulation of the early potentials by temporal attention (Correa, Lupianez, & Tudela, 2006). Correa et al. (2006) used the classic cueing paradigm with all stimuli displayed in the centre of the screen. The cues used in this experiment were the

words ‘EARLY’ and ‘LATE.’ These cues guided participants attention to the end of either short interval (450 ms; ‘EARLY’) or long interval (1450 ms; ‘LATE’). Only one cue was displayed on a trial and the target was either the letter ‘O’ or the letter ‘X.’ The participants were instructed to press left key of a button box with their left index finger for one target and to press the right key of a button box with their right index finger for the second target. Therefore, in the task, the participants were required to discriminate between different letter which demanded more perceptual processing than simple detection. Invalid trials were presented with the probability of 0.22. The valid trials were presented with the probability of 0.66. Remaining trials were catch trials where a target did not follow a cue. They demonstrated that cued target elicited a larger P1 component than the uncued target. It was the first study showing temporal attention effect on P1 component.

Research by Griffin, Miniussi, and Nobre (2002) seems to support Correa et al. (2006) suggestion. Griffin et al. (2002) conducted two experiments using cueing paradigm with centrally located cues. In the first experiment, the cues consisted of a narrow or wide cross flashed on the screen for 100 ms and they indicated the likely time interval after which a target would be presented. There was a first short interval (600 ms, relative to the cue onset) following a cue. After that interval, two patterns of concentric squares were presented simultaneously for 100 ms, one on each side. Following that there was a second, long interval (1200 ms, relative to the cue onset) after which the same pattern of concentric squares was presented simultaneously for 100 ms, one on either side. The target was a pattern of concentric squares with one of its inner squares missing. It could appear at the first or second interval and either right or left spatial location. Their second experiment used a similar paradigm with two important differences. Firstly, the target was presented only at one of the two spatial locations. Secondly, the target appeared only at one time interval. In both experiments, the participants were instructed to respond only to cued targets. Furthermore, the target required a finer

perceptual analysis due to its more complex visual features. Modulatory effect of temporal attention influenced mainly potentials associated with decision and motor response, N2 and P300.

They, also, found that the N1 increased for cued target compared to uncued targets in their first experiment over bilateral occipital electrodes. However, N1 scalp distribution was diffused and nonlateralized in contrast to N1 component recorded in the spatial attention research (Luck, 1995). Furthermore, their second experiment did not replicate this result. In both of their experiments, they did not record temporal attention effect on the P1. Spatial attention has been repeatedly shown to modulate early perceptual processing (Luck, 1995). Therefore, their results could suggest that the modulatory effect of temporal attention is different from the typically observed for spatial attention. Therefore, differences in the modulation of these two components found between temporal and spatial attention could potentially suggest differences in the mechanism used to process spatial and temporal information. For example, temporal attention may not involve perceptual preparation. Instead, it could enhance motor response which could be caused by differences in the neural representation of space and time (Lampar & Lange, 2011; Miniussi et al., 1999).

Lange, Rösler, and Röder (2003) used the temporal cueing paradigm in the auditory modality. In their experiment, participants listen to either short (600 ms) or long (1200 ms) empty intervals which beginning was signalled by white noise burst. At the end of each interval, either a standard sound or a rare target sound was presented. A rare sound differed in frequency from the standard sound and the participants' task was to respond to the rare sound. The target sound appeared on 20% of the trials and the standard sound appeared on the 80% of the trials. In their study, the auditory N1 was larger for stimuli presented at the cued interval. Later cueing studies in auditory modality also demonstrated the modulation of N1 by the temporal attention (Faugeras and Naccache 2016; Lange, Krämer, & Röder, 2006; Röder, Krämer, &

Lange, 2007; Sanders & Astheimer, 2008). Therefore, as it can be seen, temporal attention in the auditory modality has been repeatedly shown to be associated with the modulation of the early sensory-related potential. It indicates that not only late motor and decision processing related stages are modulated by orienting attention to a point in time.

Doherty, Rao, Mesulam, Nobre, and Doherty (2005) investigated whether perceptual modulations of temporal attention depend on the presence of spatial expectations. They manipulated temporal and spatial expectations independently by showing their participants a ball which moved across a screen either at a regular or irregular pace following a predictable or unpredictable path. At the right side of the screen, a ball disappeared behind the occluding band. Participants task was to notice if a ball had a black dot inside after it became visible. There were four different conditions in that study: no expectation, only spatial expectation about the location of reappearance, only temporal expectation about the time of reappearance, and combined spatiotemporal expectations. All expectations resulted in shorter RTs. The combined spatial-temporal expectation was reflected in faster RTs. Temporal attention on its own was not associated with the modulation of P1. However, when both expectancies were manipulated in concert the enhancement of perceptual processing was greater, indicated by differences in P1, than enhancement of perceptual processing recorded in response to spatial expectancy only. Rohenkohl, Gould, Pessoa, and Nobre (2014) also studied the synergistic effect of these two expectancies. In their experiment, a cue indicated the location where the response-relevant stimulus was likely to appear as well as its onset time. Unlike Doherty and colleagues (2005) the authors found an interaction between both expectancies. Temporal expectations enhanced perceptual processing only when a target was displayed at the attended location. Their results also confirmed synergistic influences of temporal and spatial expectations on the modulation of visual perception.

Lange and Roder, (2006) research aimed to study whether the temporal expectations influences behaviour within and across modalities in a similar fashion to spatial expectations that have been found to modulate the processing of stimulus across task-relevant and task-irrelevant modality. In their experiment, short (600 ms) and long (1200 ms) intervals were presented on each trial that began with a tactile stimulus. At the end of the interval either tactile or auditory target was presented. In all blocks, participants were asked to focus on a single interval and a single modality. Their results showed an enhancement of early negative deflection and faster RTs to a target presented at the end of cued in contrast to uncued intervals. This pattern was found both in task-relevant and task-irrelevant modality. Their finding indicated that early perceptual processing can be influenced by temporal attention and highlight the role of the time dimension in binding information reflected in different modalities.

1.8 Temporal orienting effect on behaviour

In the research on temporal orienting a common pattern in behavioural results can be observed. Specifically, RTs to a target presented at the end of the short interval are longer than RTs to a target appearing at the end of the long interval. Also, temporal cueing is associated with improvements in RTs to valid targets in contrast to invalid targets. However, this validity effect is typically recorded when a participant responds to a target appearing at the end of a short interval. Faster RTs to cued targets were observed not only in the simple RT tasks but also in the experiments using discrimination tasks (Chauvin, Gillebert, Rohenkohl, Humphreys, & Nobre, 2016; Correa, Lupianez, & Tudela, 2006; Coull and Nobre, 1998; Denison, Heeger, & Carrasco, 2017; Faugeras & Naccache, 2016; Johnson, Palmer, Moore & Boynton, 2020; Rohenkohl, Gould, Pessoa, & Nobre, 2014; Miniussi et al. 1999). Zanto et al. (2011) expanded these results by demonstrating similar advantages of temporal orienting in the go-no-go paradigm. They also found that older adults did not benefit from predictive information carried by cues indicating a deficit of older adults' (62-82-year-old) in temporal

orienting. In the go-no-go paradigm, participants are instructed to respond to one stimulus (Go-stimulus) and to inhibit their response to the second stimulus (No-go-stimulus; Falkenstein, Hoormann, & Hohnsbein, 1999).

Denison, Heeger, and Carrasco (2017) adapted the temporal-cueing task in their study where multiple targets appeared in succession. A cue with 75% validity indicated whether the target after the short interval or target after the long interval would be response relevant. On all trials, two target stimuli, separated by a 250 ms interval, were displayed at the same location. An auditory cue instructed the participants to orient their attention to the first or the second target or to sustain attention across trials equally. The participants were instructed to discriminate the tilt of one of the two targets. Denison et al. (2017) demonstrated that when participants oriented their attention to a cued moment in time, their perception at that point is enhanced and it leads to perception impairment at the other moments. This study demonstrated that temporal orienting is temporally selective in the sense that when it selects a point in time perception at the other moment is impaired.

These studies helped to investigate whether temporal expectations are flexibly controlled by an individual or whether they are automatic. Furthermore, these behavioural results confirm that the modulation of RTs in cueing paradigms is typically influenced by the hazard function. In a study using cues predicting target onset time with high accuracy, a participant can assume that if a target did not appear at the end of the short interval it will subsequently appear later during a trial. This information allows participants to reorient their attention towards the end of the long interval. Consequently, participants preparation increases with the flow of time resulting in a lack of differences in RTs to cued and uncued targets presented at the end of the long interval.

The effects of the hazard function are typically observed in the cue-target paradigm with varying cue-target intervals (CTI). However, these effects can be eliminated by for example changing the likelihood of a target appearing at a particular time point. Correa, Lupiáñez, and Tudela (2006) manipulated a probability of target occurrence by changing the proportion of catch trials, where no target appears after a cue. They found the typical validity effect on RTs to target presented at the end of a short time interval. However, participants in their experiment also responded significantly faster to cued targets presented after the long delay in contrast to uncued targets presented at the end of the long delay. They suggested that the presence of catch trials may cause what they called dispreparation in the participants. As a result, it could affect the reorienting process as participants could not be certain that the target will appear at the end of a long delay. Therefore, as it can be seen, the predictive temporal cues are not the only information that influences a participant's RTs and their electrophysiological response in the experiments. People are sensitive to several contingencies, inextricably embedded in the temporal attention experiments (Correa et al., 2006).

Interestingly, hazard function has been found to influence the behaviour of other species. For example, Anderson and Sheinberg (2008) conducted a study in which they compared macaque monkeys' RTs to valid and invalid targets. In their experiment, a set of 100 images of different objects was used. Each image had two different meanings depending on its position in a trial. When an image was first in a trial it indicated the likely time delay after which a second image would appear. A delay could be either short (1000 ms) or long (2000 ms) relative to the cue offset. The animals' task was to respond to the second image by pressing a button. Each image was associated with a specific temporal interval; 20% of trials were invalid where the second image followed the alternative delay. The participants learned that association over several months of the behavioural training. Correct performance on a trial was associated with a juice reward. Their results demonstrated that valid trials were associated with

faster responses compared with invalid trials. This effect was observed only for a short delay. Furthermore, the animals responded faster to images presented at the long delay suggesting that they were able to track the hazard function of the stimulus presentation.

Jaramillo and Zador (2011) designed a new paradigm to explore the influence of temporal expectation on behaviour in rats. In their experiment, they measured the RTs and accuracy of rodents participating in a detection/discrimination task that manipulated the anticipation of sounds onset. Each trial was initiated by rats poking their nose into the centre port of a three-port operant chamber. After a silent delay of random duration ranging from 250 – 350 ms a sequence of tones divided by 50 ms was presented. Each tone lasted 100 ms and its frequency was randomly chosen from 5 kHz to 40 kHz range. Two target tones were intermixed within that sequence of sounds. The target tone indicated whether a water reward is going to be provided in the left or right side-port. The 6.5 kHz target sound indicated that the water will be provided at the left port whereas 31 kHz target sound indicated that the water will be provided at the right port. The target sound replaced one of the standard sounds presented in the sequence and it could be presented either after 450 ms or 1500 ms following the first tone onset. In the first block, the target sound was presented at 450 ms on 85% of the trials. In the remaining 15% of trials, the target was presented after 1500 ms. In the next block, the proportion of trials was swapped. RTs were measured from the target onset until the moment when the animal left the centre port. The authors used only trials with early targets for their analyses. They defined valid early stimulus as a target presented at 450 ms in a block where 85% of targets were presented early. In contrast, invalid early stimulus was defined as a target presented at 450 ms in a block where only 15% of targets were presented early. Their results demonstrated that RTs to valid targets were shorter compared to the invalid targets. The animals also made fewer errors on valid trials.

1.9 CNV

ERP potential that is typically recorded in timing research is the Contingent Negative Variation (CNV). It is a negative voltage deflection that spans across the whole of the cue-target interval (CTI). It can be recorded between two stimuli and has been observed in paradigms using temporal structures described above hazard rates, rhythms, and associations. The areas located in the frontal lobe, the dorsolateral prefrontal cortex (DLPFC; Faugeras and Naccache, 2016), and motor areas (Cravo et al., 2013), were suggested to be a generator of this component. Some research has suggested that CNV reflects an approximation of the time that passed between two stimuli (Pfeuty, Ragot, & Pouthas, 2005). The CNV was first reported by Walter et al. (1964) who used the S1-S2 paradigm in their study. The S1 refers to the first stimulus from two presented in succession and it is a warning signal indicating the appearance of the second stimuli, S2. In Walter et al. (1964) study a cue, presented on each trial, was followed by a target appearing either 500 or 1000 ms later. The authors recorded a negative voltage deflection occurring between stimulus and target at the frontal electrodes' sites. However, they found that the CNV could only be recorded when the target required a button press. This potential was not recorded when the second stimulus did not necessitate a response. Thus, it first appeared that the CNV reflects a subject's preparation for the upcoming stimulus. Walter et al. (1964) suggested that it could be caused by the CNV being generated only when the temporal association between two stimuli is developed. To investigate this suggestion, Walter et al. (1964) asked their participants not to respond to a second stimulus once the temporal association was established. The CNV was recorded on those trials but this effect disappeared after 30 trials. Furthermore, when participants were given a choice whether to respond to a target or not the CNV was only recorded on the trials where participants decided to respond even though temporal association binding these stimuli was maintained on the trials where participants chose not to respond. The authors also recorded a CNV when participants

were required to only judge time interval without any related response. It indicates that the CNV may be associated not only with preparatory but also with decisional processes in the context of timing performance. A CNV also was demonstrated to be strongly affected by the differences in the predictability of events. In research where a temporal association is developed between two stimuli, a CNV peaks at the expected onset time of the stimuli or response indicating that a CNV follows the hazard function (Cravo et al, 2011; Nobre et al., 2007).

Weerts and Lang (1973) demonstrated that a CNV consists of two main components with different temporal patterns. In their study, they increased the time interval diving stimuli to more than 3s and they recorded negative voltage deflection after a cue offset time which returned to baseline. Negative voltage deflection was recorded again before the target onset. The first component was called the orienting wave and the subsequent component expectancy wave. They suggested that the early CNV could reflect cognitive processes whereas late CNV could reflect mainly the level of motor preparation. To provide a better description of the CNV later studies have tried to elicit it using a paradigm that did not involve motor response. However, in these studies participants were instructed not to respond to some extent on some of the trials. It is then possible that the recorded CNV could also reflect the processes related to the inhibition of the motor response (Mento, 2013). Therefore, to record the cognitive aspect of this ERP and to disentangle it from the motor-related processes a paradigm that requires only a mental judgment of time should be used. It would allow researchers to demonstrate whether the cognitive component of the CNV is independent of response-related processes shedding light on various influences on preparatory processes.

If a CNV could be recorded in a task that does not involve motor response it would suggest that its cognitive element is independent of the response-related processes. Conversely, if the motor response is necessary to record a CNV it should not be recorded in the study using

only mental judgement task suggesting that time perception is associated with motor action. Mento, Tarantino, Sarlo, and Bisiacchi (2013) addressed that issue in their experiment where they combined the S1-S2 paradigm and the oddball paradigm. Oddball paradigms are used to elicit an electrophysiological response to a deviant stimulus (Mento, 2013). The S1 was a red cross displayed for 500 ms and the S2 was an image of a yellow 'smile' surrounded by a black line. In this study, one of the three ISIs was presented 70% of the time whereas the remaining two deviant intervals were presented 15% of the time each. Participants were not given any specific instructions except fixating on the centre of the screen and they did not have any specific motor task to perform. According to the hypothesis a participant expectancy, potentially indicated by the recording of a CNV, should be the highest at the end of the frequent interval. The authors recorded a clear CNV for both frequent and deviant intervals which peaked at the end of the frequent interval. It indicated that over-exposition to the frequent ISI led participants to automatically develop a temporal expectation of the second stimulus. Importantly, brain source analysis demonstrated the activation of the SMA during the ISI. This ERP was called "passive CNV" and it was suggested that it could reflect a basic cognitive action-independent mechanism. This mechanism could be responsible for people's inherent ability to follow the timing of events to develop and update the internal representational model of the environment (Mento et al., 2013). Furthermore, a CNV is modulated in the explicit timing tasks in which participants are instructed to judge the duration of a stimulus or ISI (Pfeuty et al., 2005). Reviewed research demonstrates that various processes contribute to the CNV including action-related activity as well as a task-related cognitive activity.

1.10 Willed attention

As can be seen from reviewed literature, a growing number of studies have investigated the nature of cognitive processes engaged in temporal attention. In the previous literature, attention has been proposed to be divided into voluntary (also known as endogenous or top-

down) attention and automatic (exogenous or involuntary) attention. The former, in the temporal attention context, reflects an individual voluntarily orienting their attention to a specific temporal information and encoding associations present in that information. For example, in the environment, the use of endogenous temporal attention can be reflected by the encoding of information carried by yellow traffic light signalling the need to stop which allows adjusting driving behaviour. The latter does not require voluntary effort to encode temporal association which, instead, is instantiated by the properties of an event. (Mento, 2017).

The former type of attention was termed endogenous to highlight that it has a goal-directed nature in contrast to the more stimulus-driven nature of the latter (Hopfinger & Mangun, 1998; Posner, 1980). In everyday life, we may use external cues to instruct our endogenous attention. However, we also make internal choices, without external cues, of where or when to orient our attention. In most studies on endogenous attention, external cues have been used to direct participant attention towards a task-relevant target. Thus, the neural mechanisms underlying endogenous attention have been studied by attracting attention reflexively. In other words, the orienting of attention has not been guided by internal choices. Cognitive processes that are associated with these two ways of guiding the endogenous attention are different. Choosing when to orient attention is associated with conflict perception induced by competing alternatives as well as conflict resolution and selective suppression. Using cues to orient the attention does not engage the above-mentioned processes. Thus, it can be argued that to better understand endogenous attention a variation of the classic cue-target experimental paradigm is needed, and recent studies have attempted to design it (Bengson, Kelley, & Mangun, 2015; Bengson, Liu, Khodayari, & Mangun, 2020; Liu et al., 2017; Rajan et al. 2018; Taylor, Rushworth, & Nobre, 2008).

In Taylor et al.'s (2008) study, who modified Posner (1980) style paradigm, letters "L" and "R" were presented in the centre of the screen above and below a horizontal line. On the

instructed attention trials, one of these letters was highlighted instructing a participant to pay attention to either left or right side of the screen. On the choice attention trials, the horizontal line was highlighted and, upon seeing this line, participants were asked to make a choice between two sides and focus their attention there. At one of these spatial locations stream of letters appeared containing a letter "a" to which participants were required to respond. It was the first study exploring the nature of the choice-guided visual-spatial attention orienting. The authors also used a divided attention task as their comparison group. On those trials, participants were asked to attend to both sides of the screen equally. Both choice and instructed attention led to faster RTs in contrast to divided attention condition. There were no differences in RTs between the choice and instructed attention condition. However, people made more errors when they were required to make a choice. fMRI data demonstrated that choosing where to orient attention was associated with the activation of a large cluster of the medial frontal cortical regions. These regions have been previously demonstrated to be activated in the endogenous processes guiding action (Nachev, Rees, Parton, & Kennard, 2005; Passingham, Bengtsson, & Lau, 2009). Medial prefrontal regions are important areas in the network monitoring behaviour for possible conflicts. They engage other brain regions to perform goal-directed behaviour adaptations (Cohen & Donner, 2013). In Taylor et al. (2008) study, all areas which were selectively activated by deciding where to attend were located in the frontal lobe. The parietal cortex was engaged on both choice and instructed attention trials indicating that it is driven by attentional control regardless of whether attentional orienting was initiated by instruction or by decision making.

Bengson et al. (2015) used a similar paradigm to look at the temporal dynamics of choice-guided attention. In their study, one of three different cues were presented to the participants on each trial. Two of them were instructional cues and they directed a participant to orient their attention to either left or right hemifield. The third cue instructed participants to

freely choose to attend to either left or right visual field. They called that willed attention condition. The participants were required to discriminate the spatial frequency of the stimulus presented in the attended visual field with a button press. The participants were instructed to respond only if the target appeared at the expected side and to report at the end of each trial which visual field they focused on. It was the first exploration of ERP components of the choice-guided spatial attention. They found a significant difference between willed attention and instructed attention in early positive ERP component with a frontal topographic distribution occurring between 250 ms and 350 ms after the cue onset. They recorded greater positive amplitude in the willed attention condition. Bengson et al. (2015) termed that early potential the early willed attention component (EWAC). They, also, found a significant difference of broadly distributed negative component starting at 400 ms post cue and ending at 800 ms post cue and they called it the willed attention component (WAC). They suggested that EWAC might reflect the categorisation of the stimuli as a choice cue whereas WAC could reflect a decision-related process.

Liu et al. (2017) also analysed the fMRI data from Bengson et al. (2015) study. They found that the frontal lobe initiated the decision pertaining to attention allocation. It was then passed to the parietal regions for attentional resources to be deployed. Von Stein and Sarnthein (2000) noted that such interactions between distant areas in a brain are facilitated through theta frequency bandwidth. Rajan et al. (2018) results are in line with this suggestion. These authors using the data recorded in Bengson et al. (2015) study explored the frontoparietal interaction in willed attention. They found that frontal theta power was higher in the willed attention condition compared to the instructed attention condition. Furthermore, Rajan et al. (2018) theta increase coincided with the WAC component reported by Bengson et al. (2015). These findings suggest that theta facilitates frontoparietal interactions during decision-making and consequent attention orienting. Furthermore, Cohen and Donner (2013) used Simon's task to explore the

electrophysiological activity during response conflict. Cognitive processes involved in response conflict include conflict detection, action selection, and suppression. Therefore, they overlap with the cognitive processes involved in willed attention. Cohen and Donner (2013) found that response conflict was modulated in the theta band activity in the time interval between stimulus onset and manual response which support the involvement of theta frequency in the willed attention. Furthermore, Rajan et al. (2018) compared the temporal dynamics of willed versus instructed spatial attention. In the spatial attention research, the power of posterior alpha (8-12Hz) was demonstrated to decrease over the ipsilateral cortex and increase over the contralateral cortex. This is known as alpha power lateralisation and it was used by Rajan et al. (2018) as an index of attentional orienting. They found that willed attention orienting was delayed by 460 ms compared to instructed attention orienting. This probably can be explained by the involvement of the additional cognitive processes related to decision-making.

1.11 Rationale and aims

Perception of time underlies perceptual, motor, and cognitive activities allowing an individual to anticipate changes in the environment to adjust behaviour. It comprises various aspects including implicit/explicit and sub/supra second timing. Furthermore, this ability is shared across species and plays a crucial role in survival. Several brain structures were demonstrated to be involved in the perception of time including cerebellum, the basal ganglia, prefrontal cortex and the supplementary motor area (Coull et al., 2011). However, there is no accepted description of the networks that support timing. The system responsible for the perception of time is susceptible to attentional control (Nobre & Rohenkohl, 2014). In the introduction three types of temporal biases, concerned with short temporal intervals, have been discussed with the focus on temporal associations. Research on temporal associations is often using paradigm introduced by Posner (1980). The process of directing attention in the research

on temporal associations is called orienting of attention. It was suggested to rely on IPS, the anterior inferior parietal lobule, and inferior premotor cortex. This network was shown to have left hemisphere dominance and more inferior location compared to the network involved in the orienting of spatial attention (Nobre & Rohenkohl, 2014). Temporal orienting studies demonstrated that people respond faster to cued target than uncued target indicating that temporal attention is under flexible and voluntary control. This effect is visible across a variety of tasks including go/nogo, simple RT task, and discrimination task, as well as within and across modalities (Correa et al., 2006; Lange & Roder, 2006; Miniussi et al., 1999; Zanto et al., 2011). The electrophysiological results of these studies demonstrated that a negative voltage deflection called CNV can be recorded using all described temporal biases. In the auditory modality, the temporal attention has modulated early perceptual processing. In the visual modality, this effect was less clear (Nobre & Rohenkohl, 2014). However, still, relatively few studies investigated the neural modulatory mechanisms of temporal attention. In most of the studies on temporal orienting external cues have been used to direct participant attention. However, in everyday life, we also make internal choices, without an external cue, of when to orient our attention. Recent studies have attempted to develop a new paradigm in the visual-spatial attention aiming to develop the scope of the classic cueing paradigm. This paradigm includes the willed attention condition where a participant needs to choose where to attend (Rajan et al., 2018). The current study draws on the distinctions made between instructed and willed visual-spatial attention. It aims to shed light on whether and how willed temporal attention affects behaviour and whether this is different from instructed temporal attention by looking at both behavioural data as well as EEG.

In the current study, attention could be either instructed or willed. In the instructed attention condition two cues were presented to a participant. The appearance of one of these cues instructed a participant to anticipate either a short (800 ms) or a long (2000 ms) interval

separating cue and the target onset times. In the willed attention condition, only one cue was presented to the participants on a trial. The appearance of this cue instructed participants to choose for themselves after which time interval they want to anticipate the target. In the present experiment, there were 3 independent variables; each had two levels. The first was called Cue Type and it referred to the attention type; therefore, it could be either instructed or willed. The second was called Expected Cue Length. It reflected the expectancy, induced by a cue, of the interval between cue onset and the target onset. In the experiment, it was divided into Expected Cue Length short (800 ms) and Expected Cue Length long (2000 ms). The third independent variable was called Target. It indicated the target onset time relative to cue onset time; therefore, it also was referred to as Target short (800 ms) or Target long (2000 ms) (see section 2.4 Design and materials for details). Therefore, the validity of a trial can be seen as a combination of Expected Cue Length and Target. For example, if Expected Cue Length was short and Target was also short it was a valid trial. Alternatively, if Expected Cue Length was short but Target was long it was an invalid trial.

1.12 Hypotheses

1.12.1 Behavioural data hypotheses

1. I expect to see the main effect of the Target such that RTs to the Target at the long CTI should be faster than those to the Target at the short CTI.

2. I expect to see the main effect of Cue Type – that RTs will differ between instructed and willed conditions. The willed attention condition requires additional cognitive effort associated with the decision-making process. Thus, willed attention condition may be associated with longer RTs. Alternatively, willed attention decisions may result in an increased attentional focus leading to faster responses to targets following willed compared to instructed cues.

3. I expect an interaction between Cue Type and Target. The possible increased amount of time that decision processing takes, or the increase in attentional focus as a result of willed attention, will likely result in RTs being different for willed and instructed attention when the Target is long compared to short.

1.12.2 EEG data hypotheses

ERPs include CNV, P1, N1; in the current experiment, I will analyse the amplitudes of these ERPs

4.a I expect to see the main effect of the Expected Cue Length such that ERPs will be different when the Expected Cue Length is short compared to long. This analysis is limited to when Target matches expected cue length (i.e. not invalid trials).

4.b I expect to see a main effect of the Cue Type – that ERPs will be different for willed vs instructed attention. This analysis includes Target type short and long, but only when Expected Cue Length matches (i.e. not invalid trials).

4.c I expect an interaction between Cue Type and Expected Cue Length such that ERPs for willed and instructed attention will differ when Expected Cue Length is short compared to long. This analysis includes Target type short and long, but only when Expected Cue Length matches (i.e. not invalid trials).

4.d I expect an interaction between Expected Cue Length and Target. This analysis only includes trials with short Target. That is, a difference in ERPs for willed and instructed attention when Target is short and Expected Cue Length is short (valid trial), compared to when Expected Cue Length is long, but the Target type is short (invalid trial).

5. The analysis of theta oscillations will be cue-locked and compare willed vs instructed attention. The analysis will be separated for Expected Cue Length short and long. I expect theta power to be larger in willed compared to instructed Cue Type. However, I will take the data-driven approach; therefore, I do not make further predictions of when in the CTI this effect will be present.

2. Methods

2.1 Pre-registration process and impact of COVID

This study was preregistered at the Open Science Foundation website before the data collection started (registration documents can be found here: https://osf.io/z2r69/ or in Appendix A). The OSF is a free web application which saves research details and makes them discoverable (Nosek, Ebersole, DeHaven, & Mellor, 2018). On that website, a detailed design plan, sample size rationale, pre-processing and statistical analyses, as well as data exclusion criteria were described. Furthermore, all hypotheses were listed, and the experiment file was uploaded. Preregistration of a study details is committing researcher to the methodology and analyses without knowledge of the study results. Therefore, analytic approach cannot be changed when conducting a study which limits the influence of motivation, memory, or reasoning biases on the research process. Thus, the preregistration process aims to increase openness and integrity of the study and it has been shown to increase the replicability of a study findings (Nosek, et al., 2018). Consequently, preregistration of the study details is important step in conducting research to a high academic standard.

2.2 Sample size rationale

An priori power analysis (G*Power; Faul, Erdfelder, Lang, & Buchner, 2007) was conducted to estimate the required sample size using small-to-medium effect size (f = 0.175) for a 2x2x2 interaction (based on the ERPs) with power at 95%. A moderate correlation between measures was assumed (r = .5). No sphericity correction was applied as no factor had

more than two levels. The power analysis resulted in a sample size of 46 participants with an actual power of 0.95. The rejection criteria analysis was performed before, and separately to, any analysis of effects.

2.3 Participants

The experimental protocol was approved by the Middlesex University Research Ethics Committee. Thirteen participants recruited from the Middlesex University community or word of mouth took part in the experiment. Participants were rewarded with either 15 pounds of Amazon vouchers or course credit points. All participants gave informed written consent prior to the recording session. Participants were required to understand basic English to the degree that they can follow instructions. Both right and left-handed people with normal or corrected vision were accepted for participation in the current study. Data from two participants were excluded due to the high number of errors and the number of usable trials not meeting the threshold (see section 2.6 Data exclusion criteria for details). Therefore, data from 11 participants (6 females; 5 males; mean age 23.8; standard deviation 3.91) were analysed.

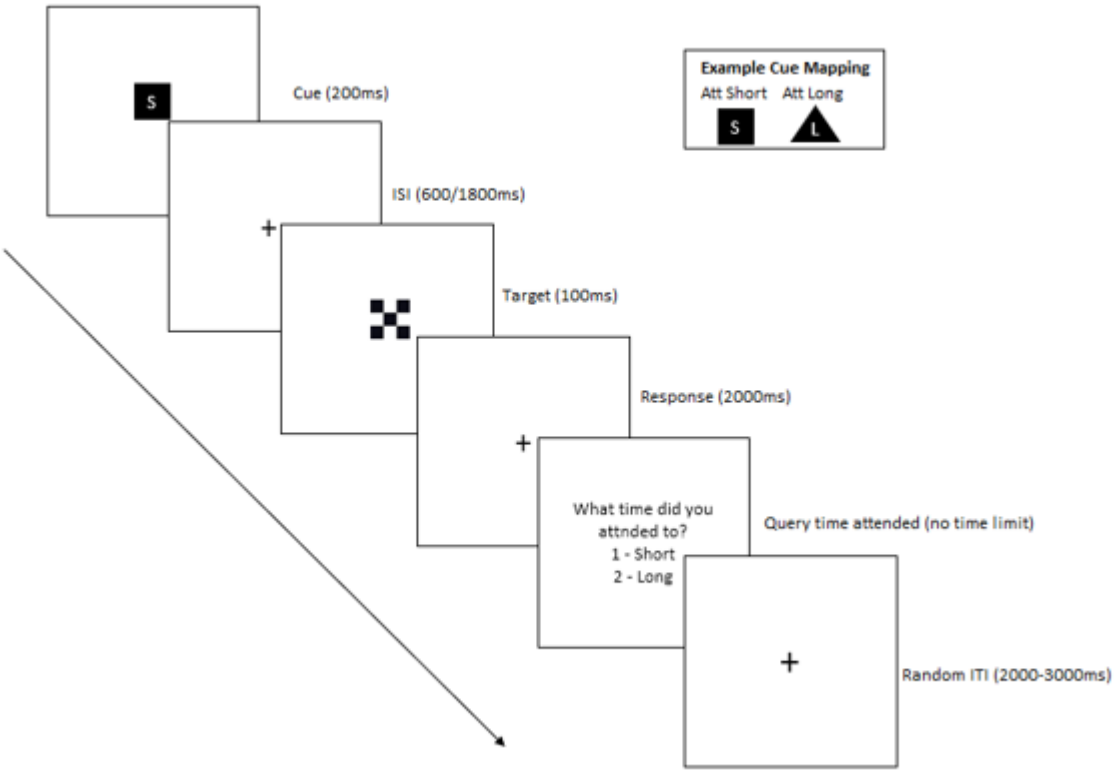
2.4 Design and materials

In the current experiment, there were 2 dependent variables, RT and amplitude. Two separate PCs were used; one recorded the EEG data using Active View software (BioSemi) and the other recorded the behavioural data and presented the stimuli. The presentation of stimuli and behavioural data recording was carried out by E-Prime 3 software (Psychology Software Tools ltd). All stimuli were presented on a white background in the centre of the screen on a 25-inch monitor located in a sound-attenuated booth. This monitor was connected to the PC that run stimuli presentation software. Furthermore, this PC sent markers to the second PC that recorded EEG data. A voice-key connected to the TactAmp (Dancer Design, Ltd) was used to record the participants RTs. The voice-key onset is recorded as an event in E-Prime and RT is calculated as the duration of the time between target offset and voice-key

onset. The RTs were time-stamped by the E-Prime connected to Chronos (Psychology Software Tools ltd). Furthermore, Chronos sent timestamped events to the PC recording EEG data. Chronos allows the accurate collection of responses with ms accuracy.

In the current study, attention could be either instructed or willed. The blocked design was used; therefore, these two attention types were presented in separate blocks. In the instructed attention condition, each trial began with one of two cues (see Figure 1 for a description of events in a trial). Each cue consisted of a geometric shape and was flashed on the screen for 200 ms. The appearance of one of these shapes instructed a participant to anticipate either a short (800 ms) or a long (2000 ms) interval between a cue and the target onset times. The meaning of the shapes was counterbalanced across participants (see Figure 1 for example cue mapping). Furthermore, each shape used to cue a participant had a letter inside. This letter could be either 'S' indicating a short interval or 'L' indicating a long interval. The target consisted of checkerboard flashed on the screen for 100 ms. Two possible intervals dividing cue and target onset were presented in the randomised order. At the end of each trial, the participants were required to report which time interval they attended to by pressing one of two buttons on a standard keyboard, using their dominant hand (1 – short, 2 – long). Trials were separated from each other by a random inter-trial interval ranging from 2000 ms to 3000 ms. In the willed attention condition, the design was identical except for the following. Only one shape was presented to the participants on a trial (see Figure 2 for a description of events in a trial and example cue mapping). This shape had a letter 'C' inside which meant choice. The appearance of this cue instructed the participants to decide for themselves after which time interval they want to anticipate the target.

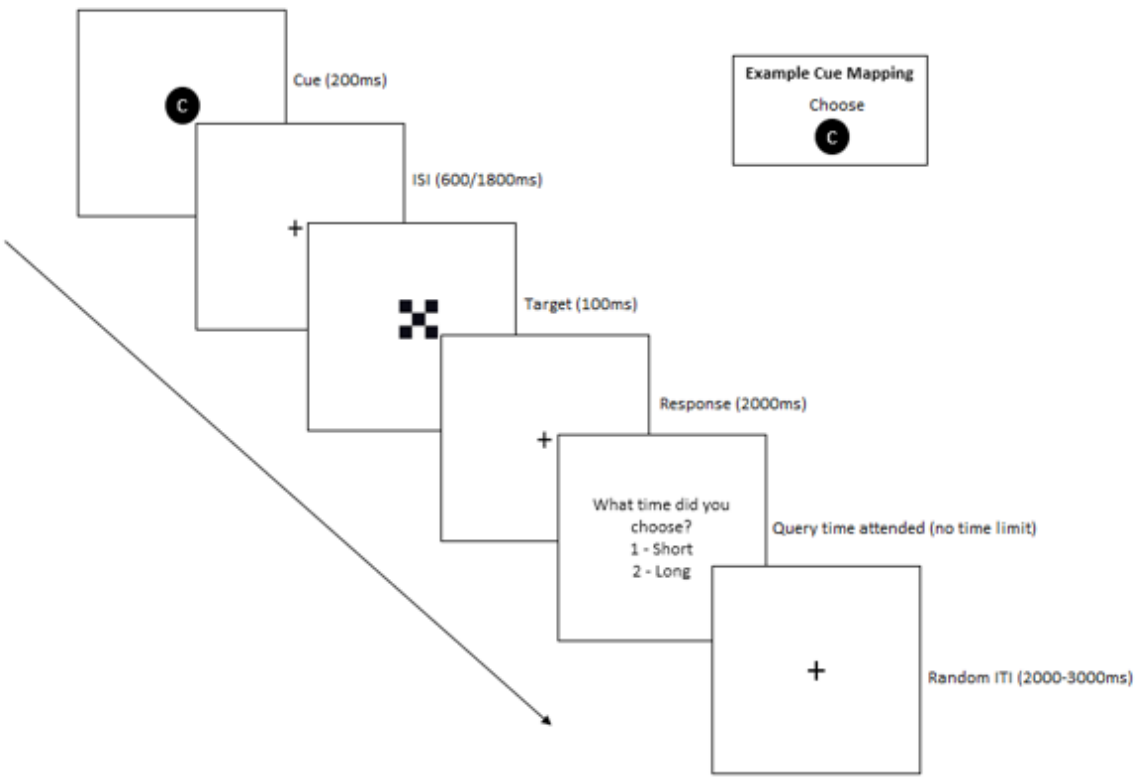
Figure 1. Instructed Attention



Therefore, as seen in figure 1 and figure 2, there were 3 independent variables in the current experiment; each had two levels. The first was called Cue Type and it referred to the attention type, therefore, it could be either instructed or willed. The second was called Expected Cue Length and it reflected the expectancy of the interval separating cue onset and the target onset induced by a cue. In the experiment, it was divided into Expected Cue Length short (800 ms) and Expected Cue Length long (2000 ms). The third independent variable was called Target and it indicated the target onset time relative to cue onset time. Therefore, it also was referred to as Target short (800 ms) or Target long (2000 ms). Consequently, the validity of a trial can be seen as a combination of Expected Cue Length and Target. For example, if Expected Cue Length was short and Target was also short it was a valid trial. Alternatively, if Expected Cue Length was short but Target was long it was an invalid trial. Whether the Expected Cue Length was short or long in the willed attention condition was determined using a participant report. If at the end of a trial a participant pressed 1 it meant that the Expected

Cue Length was short, alternatively, if a participant pressed 2 it meant that the Expected Cue Length was long. Therefore, the validity of a trial in the willed attention condition was determined using a participant report.

Figure 2. Willed Attention



Each participant performed 8 blocks of trials; 4 blocks of the instructed attention trials and 4 blocks of the willed attention trials. These blocks were presented in the alternating order. The order of presentation was randomised across participants. Each block consisted of 66 trials in total. In the instructed attention condition 11 of these trials were valid for each Expected Cue Length (e.g. cue indicates short interval and the target appears after 800 ms), 11 trials were invalid for each Expected Cue Length (e.g. cue indicates short interval, but target appears after 2000 ms), and 22 trials were catch trials where target did not follow a cue. Therefore, the probability of different condition presentations was equated. In the willed attention condition, each block contained 22 catch trials. However, the proportion of valid and invalid trials were unknown before the experiment as it depended on a participant's choice. During the

experiment, the number of correct responses to valid Targets in the willed attention condition was counted. If this number was lower than 40 for either Target short or long, then a participant took part in an extra block of willed attention trials.

2.5 Procedure

Participants were seated approximately 60 cm in front of the monitor in a dimly lit and sound-attenuated booth. Before the recording, participants completed 24 practice trials. They were informed, at the beginning of the experiment about the temporal relationship between stimuli. They were asked to maintain visual fixation on a centre of the screen indicated by a small cross. The participants were also asked not to use any specific strategy when choosing which time interval to attend. Participants' task was to respond vocally by saying "pa" into the voice key as quickly and as accurately as possible following the onset of the target. At the end of each trial, the participants were required to report which time interval they attended to by pressing one of two buttons on a standard keyboard, using their dominant hand (1 – short, 2 – long). Furthermore, only targets presented on the valid trials were response relevant. In other words, the participants were asked to focus 100% of their attention on the cued or chosen interval and only respond to the target if it was presented after this interval (only when Expected Cue Length and Target matched). Therefore, there should be a minimal spread of attention towards the unattended interval. The experiment took approximately 1.5 – 2h to complete. At the end of each block, the feedback was provided containing a participant's average response time, number of errors, and the number of correct responses in the last block. Participants were also asked if they want to take a short break.

2.6 Data exclusion criteria

Only trials were participants correctly responded to a valid target or correctly ignored an invalid target were used for the analyses. In other words, a participant's response, Expected Cue Length and Target onset time needed to be congruent for that trial to be analysed. For

example, in the instructed attention condition, trials where participants were instructed to pay attention to the short delay, and they responded to the target appearing at the end of long delay were not used in the analyses (see Table 1 for examples of the trial types). Similarly, in the willed attention condition, trials where a participant responded to a Target short, but they indicated that they decided to orient their attention towards the long delay were not used in the analyses (see Table 2 for examples of the trial types).

Table 1. Instructed attention condition - example of the trial types.

	Expected Cue Length (short/long)	Target onset time 800/2000 ms	Participant's Response	Time interval attended indicated at the end of the trial (1 – Short 2 – Long)	Used in the analysis
Valid long trial	Long	2000 ms	Yes	2	Yes
Invalid long trial	Long	800 ms	No	1	No
Valid short trial	Short	800 ms	Yes	1	Yes
Invalid short trial	Short	2000 ms	No	2	No

Data from participants whose performance fall below the threshold (<70% accuracy) was rejected from the experiment. Data was trimmed to exclude any responses below 100 ms and 2.5 SD above each participant mean RTs (across all conditions) as these responses are likely to be made by accident. A participant's data were not included in any of the analyses if they missed 20% or more of targets or respond to 50% or more catch trials as well as if they did not have 20 usable trials, after exclusion criteria analysis, in each condition. Lastly, trials with excessive muscle or body movements and with excessive eye movements or blinks related artefacts were removed.

Table 2. Willed attention condition – examples of the trial types

	Target onset time 800/2000 ms	Participant's Response	Time interval attended (1 – Short 2 – Long)/ Expected Cue Length	Used in the analysis
Valid long trial	2000 ms	Yes	2	Yes
Invalid long trial	800 ms	No	2	Yes
Valid short trial	800 ms	Yes	1	Yes
Invalid short trial	2000 ms	Yes	1	No

2.7 EEG recording and pre-processing analysis

EEG was recorded from 64 scalp electrodes using Biosemi Active Two system with a sample rate of 2048 Hz. EEG was referenced to the CMS-DRL (common mode sense-driven right leg). The horizontal electrooculogram (HEOG) was recorded from the outer canthi of the eye. Data were processed off-line using Brain Vision Analyser (Brain Products GmBH). The continuous EEG data were filtered with a 0.1 Hz high pass filter and 40 Hz low pass filter, as well as a 50 Hz notch. Data was re-referenced to a common average. Blinks were identified and corrected using an ICA as well as manual component inspection. Data were then segmented.

Target locked ERPs investigating the P1 and N1 were segmented into 400 ms intervals including 100 ms pre-stimulus onset, and 300 ms post-stimulus onset. Data were segmented separately for long and short Targets. A 100 ms pre-stimulus baseline correction was used. Analysis of the CNV was cue locked and it segmented the data into 1200 ms and 2400 ms epochs for Target short and Target long conditions respectively which included the CTI and 200 ms pre-cue and 200 ms post target onset. A 200 ms pre-cue onset baseline correction was used. In the time-frequency analysis, the epoch length in the Target short condition was -1500 to 1500 ms and in the Target long condition was -1500 to 2700 ms. A 100 ms pre-stimulus

baseline correction was used. Each segment was analysed using a Complex Morlet wavelet (c = 4) between 1 Hz and 20 Hz in 30 logarithmic steps increments. The wavelet analysis was baseline corrected from -1150 ms to -350 ms before stimulus onset on each trial giving baseline correction length of 800 ms. Participants' EEG recordings were checked for artefacts with an automatic Brain Vision Analyser algorithm. Bad channels were interpolated using topographical interpolation. Epochs were voltage exceeded ± 100 μV were discarded. Data was then average separately for each participant and condition. The averaged data was exported for further analysis. After the data exclusion and rejection of trails with incorrect behavioural responses, there were on average 41 of usable trials per condition in P1 and N1 averaging process (ranging from 35 to 50) and 40 usable trials per condition in CNV averaging process (ranging from 34 – 48).

2.8 Analyses plan

2.8.1 ERPs analyses

For the P1 component, a peak was defined as the largest positive amplitude averaged at PO7 and PO8 electrodes and across all conditions between 60 and 140 ms (Miniussi et al., 1999). The peak of P1 was detected at 86 ms for PO7 electrode and at 84 ms for PO8 electrode. Mean amplitudes were then extracted for each condition encompassing 20 ms either side of these peaks. For the N1 component, the peak was defined as the greatest negativity, averaged at PO7 and PO8 electrodes and across all conditions between 100 and 200 ms (Miniussi et al., 1999). The peak of N1 was detected at 141 ms for PO7 electrode and at 138 ms for PO8 electrode. Mean amplitudes were then extracted for each condition encompassing 20 ms either side of these peaks. The CNV was analysed by extracting the mean amplitudes from 200 ms pre-Target interval at Fz and Cz electrodes for each condition (Cravo et al., 2011; Faugeras & Naccache, 2016).

2.8.2 Time-frequency analysis

The analysis of theta oscillations will be cue-locked and compare willed vs instructed attention separately. It was based on Fz and Pz electrodes. The analysis will be separated for Expected Cue Length short and long. For Expected Cue Length short, all Target types (short, long) will be included. For Expected Cue Length long, Target type long will be included, but Target type short excluded in the analysis. To explore differences in amplitude between conditions, across different frequencies during the CTI, I took the data-driven approach. Therefore, I did not choose a specific region within the CTI for the analysis.

2.9 Statistical analysis

Several repeated measures ANOVAs were conducted to test the predictions pertaining to the ERPs (see section 3. Results for details). In the time-frequency analysis extracted amplitudes values had 5530 time samples in the long CTI and 3072 time samples in the short CTI. Data extracted for both long and short CTI had 30 layers reflecting different frequencies ranges in the time-frequency matrix. Therefore, analysis at each electrode contained 165 900 time-frequency points for the analysis of the long CTI for each condition and 92 160 time-frequency points for the analysis of the short CTI for each condition. It gave the total number of 1 032 240 time-frequency points for each participant. I conducted a total number of 516 120 paired sample t-tests on the mean amplitude values.

To analyse and visualise this data R script was used. This script extracted amplitude values for corresponding time-frequency points in both willed and instructed attention conditions for all participants used in the analysis. Subsequently, it conducted a paired sample t-test comparing these two samples and stored results in the separate vector. R repeated that process until the last time-frequency point. Due to the high number of comparisons, it was likely that the results would contain false positives, nonetheless, methods often used to correct

for multiple comparisons would likely produce false negatives. Therefore, the False Discovery Rate (FDR) method was used to correct the resulting p-values. The resulting pFDR < .05 were plotted on a contrast map. One colour on that map was assigned to significant values and the other colour was assigned to non-significant values. This method would allow to identify regions within the time-frequency matrix that differed significantly between conditions (Silas, Tipple & Jones, 2019).

3. Results

3.1 Behavioural results

RTs were averaged across conditions (see section 2.7 EEG recording and pre-processing analysis for exact numbers of trials per condition) and subsequently they were subjected to 2 x 2 repeated measures analysis of variance (ANOVA) with Cue Type (willed, instructed) and Expected Cue Length (short, long) as factors. The ANOVA on RTs revealed no main effect of either Cue Type, $p = .208$, $\eta p^2 = .154$ or Expected Cue Length, $p = .786$, $\eta p^2 = .008$. A Cue Type x Expected Cue Length interaction was also not significant, $p = .897$, $\eta p^2 = .002$ (see Figure 3 for the pattern of results). Therefore, no advantages in reaction times as a function of Cue Type or Target onset time were found in the current study (Hypotheses 1 – 3).

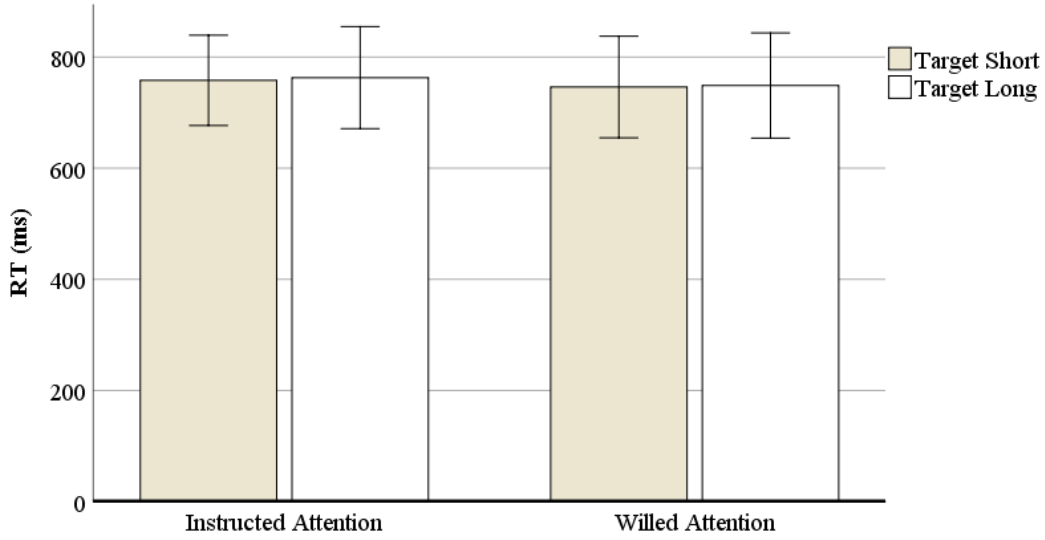


Fig. 3 Mean RT at short and long Target onset times and for Instructed and Willed Attention

3.2 ERP results

3.2.1 P1 and N1 analyses

Target stimulus elicited typical early visual potentials, P1 and N1, over two posterior electrode sites, PO7 and PO8 (see Figure 4). Amplitude changes were subjected to 2 x 2 x 2 repeated measure ANOVA with Cue Type (willed, instructed), Expected Cue Length (short, long), and Electrode (PO7, PO8) as factors to test the hypotheses 4.a, 4.b, and 4.c regarding the main effect of the Expected Cue Length short, the main effect of Cue Type, as well as their interaction. These analyses included Target type short and long, but only when Expected Cue Length matched that is only valid trials. Separate ANOVAs were conducted for P1 and N1.

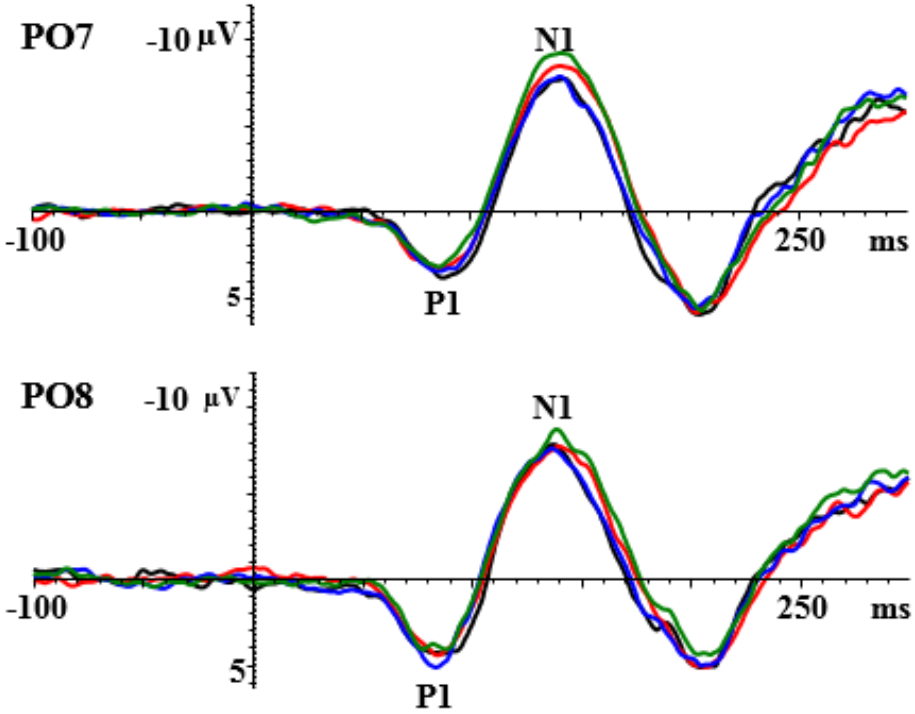


Fig. 4 Grand-averaged waveforms (n = 11) recorded in the instructed attention condition at Target short (black ERP) and Target long (red ERP) and in the willed attention condition at Target short (blue ERP) and Target long (green ERPP) at posterior electrodes sites PO7 and PO8. These ERPs include Target type short and long, but only when Expected Cue Length matched. Therefore, only valid trials are presented here. Vertical lines represent the target stimulus onset time preceded by 100 ms baseline and followed by 300 ms post-stimulus period.

The ANOVA on mean amplitudes of P1 potential revealed no main effect of Cue Type, $p = .876$, $\eta p^2 = .003$, no main effect of Expected Cue Length $p = .260$, $\eta p^2 = .125$, as well as no main effect of Electrode, $p = .509$, $\eta p^2 = .045$. Furthermore, Cue Type x Expected Cue Length $p = .477$, $\eta p^2 = .052$, Cue Type x Electrode, $p = .966$, $\eta p^2 < .001$, Expected Cue Length x Electrode, $p = .771$, $\eta p^2 = .009$ interactions were also not significant. The ANOVA on mean amplitudes of N1 potential revealed no main effect of Cue Type, $p = .937$, $\eta p^2 = .001$, no main effect of Expected Cue Length, $p = .540$, $\eta p^2 = .039$, and no main effect of Electrode, $p = .567$, $\eta p^2 = .034$. Furthermore, Cue Type x Expected Cue Length, $p = .548$, $\eta p^2 = .037$, Cue Type x Electrode, $p = .419$, $\eta p^2 = .066$, and Expected Cue Length x Electrode, $p = .214$, $\eta p^2 = .150$ interactions were also not significant. These results indicate that there were no differences between willed and instructed attention on amplitude of P1 and N1. Furthermore, the amplitudes of P1 and N1 were not different between short and long intervals.

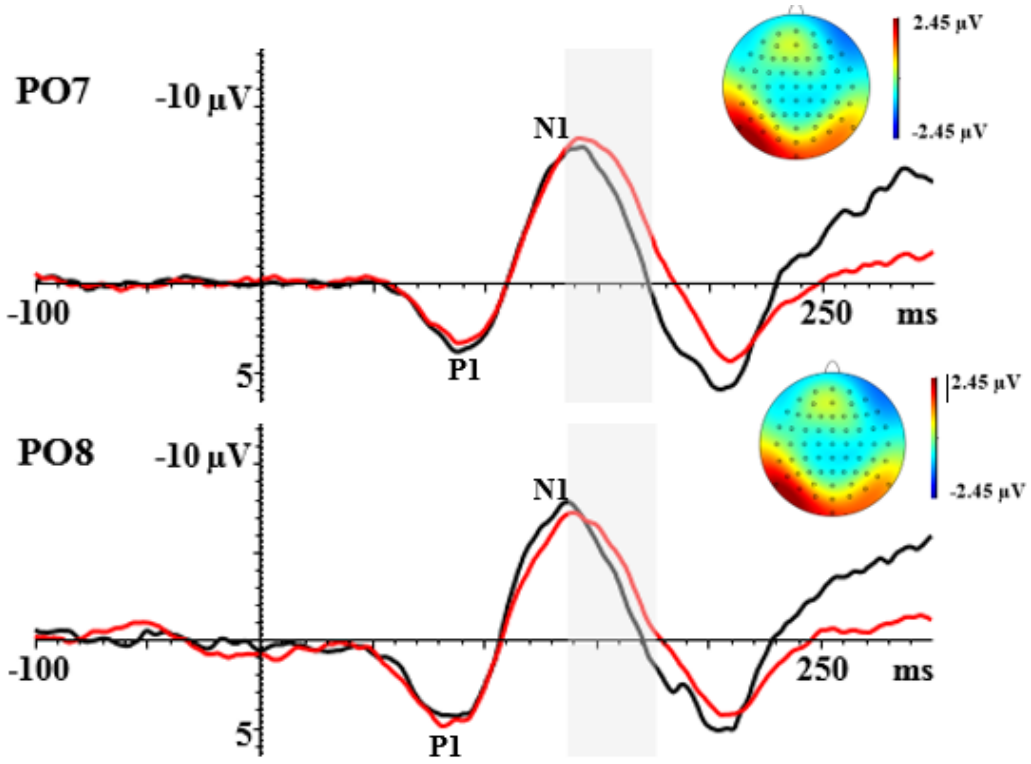


Fig. 5 Grand-averaged waveforms ($n = 11$) recorded in the instructed attention condition for Expected Cue Length short (black ERP) and Expected Cue Length long (red ERP) at posterior electrodes sites PO7 and PO8. These ERPs only include trials with Target type short. Therefore, valid and invalid

trials are compared here. Vertical lines represent the target stimulus onset time preceded by 100 ms baseline and followed by 300 ms post-stimulus period. This figure includes topographical maps of the difference waves for 140 ms to 180 ms time interval.

To test the effect of Target validity (Hypothesis 4.d), mean amplitudes were subjected to 2 x 2 x 2 repeated measure ANOVA with Cue type (willed, instructed), Expected Cue Length (short, long), Electrode (PO7, PO8) as factors. This analysis only included trials with Target type short. Therefore, it compared ERPs elicited by valid and invalid targets for both types of attention at two electrode sites. Separate ANOVAs were conducted for P1 and N1.

The ANOVA on mean amplitudes of P1 potential revealed no main effect of Cue Type, $p = .570$, $\eta p^2 = .033$, no main effect of Expected Cue Length $p = .738$, $\eta p^2 = .012$, and no main effect of Electrode, $p = .412$, $\eta p^2 = .068$. Furthermore, Cue Type x Expected Cue Length, $p = .493$, $\eta p^2 = .048$, Cue Type x Electrode, $p = .544$, $\eta p^2 = .038$, and Expected Cue Length x Electrode, $p = .163$, $\eta p^2 = .185$ interactions were non-significant. The ANOVA on mean amplitudes of N1 potential revealed no main effect of Cue Type, $p = .745$, $\eta p^2 = .011$, no main effect of Expected Cue Length, $p = .669$, $\eta p^2 = .019$, and no main effect of Electrode, $p = .605$, $\eta p^2 = .028$. Also, Cue Type x Expected Cue Length, $p = .785$, $\eta p^2 = .01$, Cue Type x Electrode, $p = .929$, $\eta p^2 < .001$, and Expected Cue Length x Electrode, $p = .129$, $\eta p^2 = .215$ interactions were non-significant. These results indicate that there were no differences between valid and invalid trials on amplitudes of P1 and N1 (see Figure 5 and Figure 6 for details).

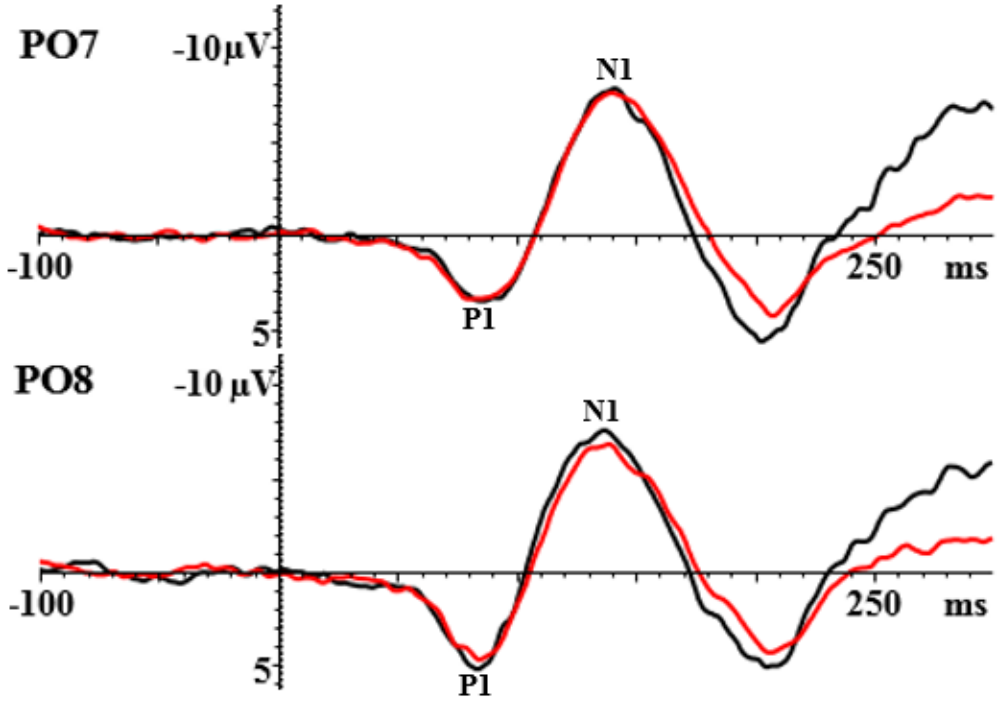


Fig. 6 Grand-averaged waveforms (n = 11) recorded in the willed attention condition for Expected Cue Length short (black ERP) and Expected Cue Length long (red ERP) at posterior electrodes sites PO7 and PO8. These ERPs only include trials with Target type short. Therefore, valid and invalid trials are compared here. Vertical lines represent target stimulus onset time preceded by 100 ms baseline and followed by 300 ms post-stimulus period.

3.2.2 CNV

Amplitude changes were subjected to the 2 x 2 x 2 repeated measure ANOVA with Cue Type (willed, instructed), Expected Cue Length (short, long), and Electrode (Fz, Cz) as factors to test the hypotheses 4.a, 4.b, and 4.c. This analysis included Target type short and long, but only when Expected Cue Length matched that is only valid trials. There was no main effect of Cue Type, p = .266, ηp^2 = .122, and no main effect of Electrode, p = .552, ηp^2 = .037. Furthermore, no Cue Type x Expected Cue Length interaction, p = .679, ηp^2 = .018, no Cue Type x Electrode interaction, p = .381, ηp^2 = .077, and no Expected Cue Length x Electrode interaction, p = .138, ηp^2 = .207 were recorded. Therefore, these results indicate that the amplitude did not differ depending on the Cue Type. However, there was a main effect of the Expected Cue Length, p = .049, $F(1, 10)$ = 5.04, ηp^2 = .335 indicating that CNV was more negative in the short CTI compared with long CTI (see Figure 7 and Figure 8 for details).

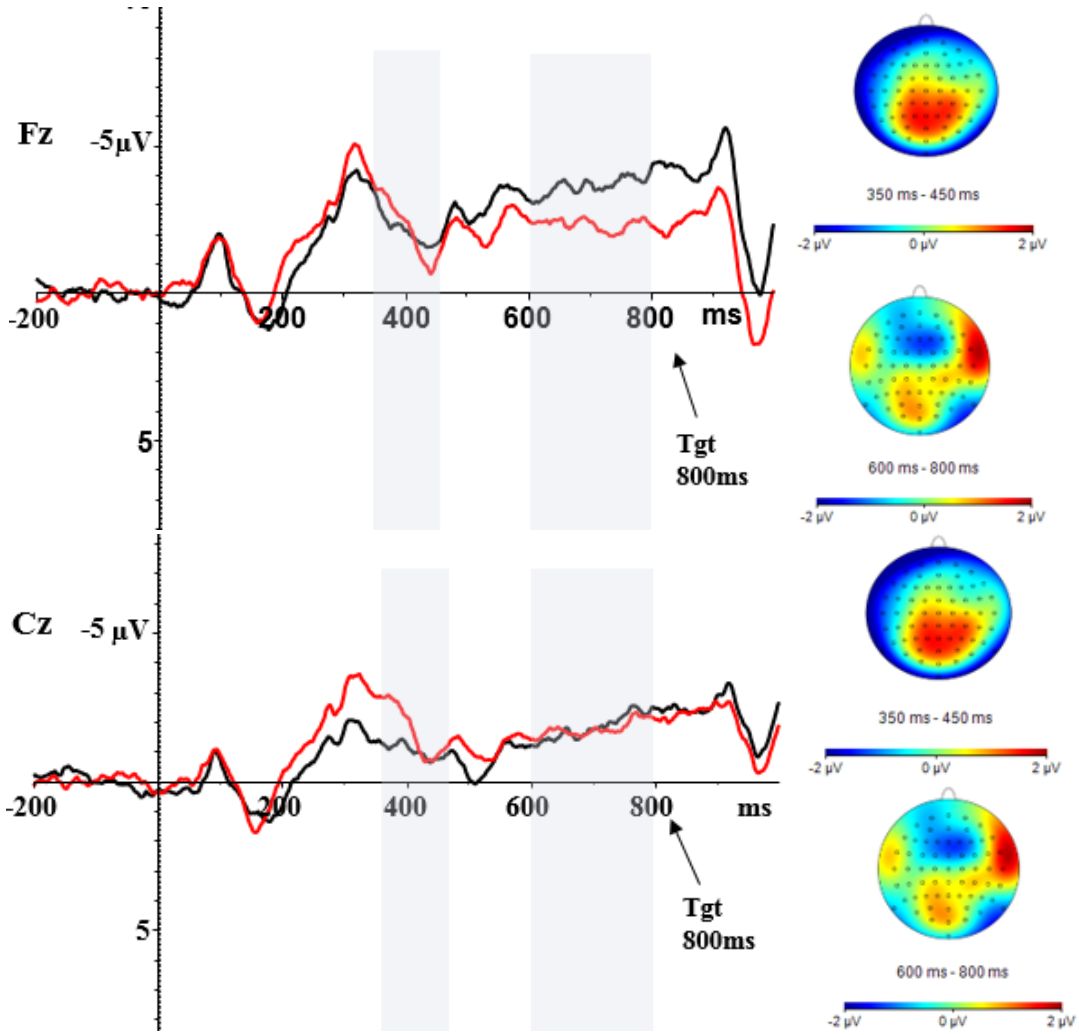


Fig. 7 Grand-averaged waveforms (n = 11) for willed attention (red ERP) and instructed attention (black ERP) at two electrode sites Fz and Cz. These ERPs include only valid trials. Vertical lines represent cue onset time preceded by 200 ms baseline and followed by 600 ms post-stimulus period. This figure includes topographical maps of the difference waves at each electrode and for 350 – 450 ms interval and for 600 – 800 ms interval.

To further analyse the Expected Cue Length main effect amplitude changes were subjected to the 2 x 2 repeated measure ANOVA with Expected Cue Length (short, long), and Electrode (Fz, Cz) as factors. Separate analyses were conducted for each Cue Type. In the instructed attention condition, there was no main effect of Expected Cue Length, p = .087, F(1, 10) = 3.61, ηp^2 = .265, no main effect of Electrode, p = .367, ηp^2 = .082, and no Expected Cue Length x Electrode interaction, p = .185, ηp^2 = .169. In the willed attention condition, there was no main effect Expected Cue Length, p = .165, ηp^2 = .193, no main effect of Electrode, p = .849, ηp^2 = .004, and no Expected Cue Length x Electrode interaction, p = .277, ηp^2 = .117.

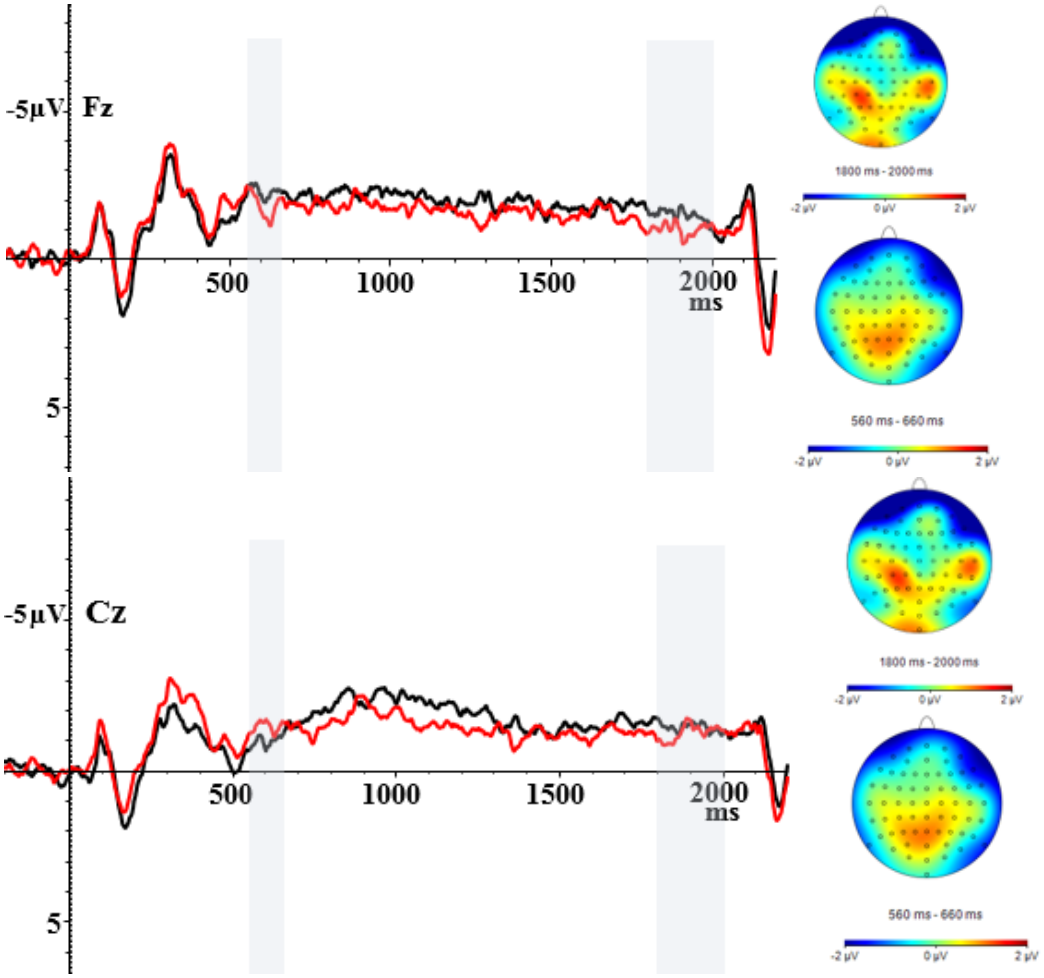


Fig. 8 Grand-averaged waveforms (n = 11) for willed attention (red ERP) and instructed attention (black ERP) at two electrode sites Fz and Cz. These ERPs include only valid trials. Vertical lines represent cue onset time preceded by 200 ms baseline and followed by 1800 ms post-stimulus period. Target was presented at 2000 ms. This figure includes topographical maps of the difference waves at each electrode and for 560 – 660 ms interval and for 1800 – 2000 ms interval.

Following visual inspection of the CNV, mean amplitudes for the time interval between 350 – 450 ms were extracted in the short CTI and for the time interval between 560 – 660 ms in long CTI (see Fig. 7 and Fig. 8 for details). Two 2 x 2 repeated measure ANOVAs were conducted, one for each valid CTI, with Cue Type (instructed, willed) and Electrode (Fz, Cz) as factors. In the short CTI, there was no main effect of Cue Type, p = .113, ηp^2 = .232 and no main effect of electrode, p = .300, ηp^2 = .107. Therefore, this analysis demonstrated medium effect size. Furthermore, Cue Type x Electrode interaction was also not significant, p = .420, ηp^2 = .066. In the long CTI, there was no main effect of Cue Type, p = .621, ηp^2 = .025, no

main effect of Electrode, p = .443, ηp^2 = .060, and no Cue Type x Electrode interaction, p = .397, ηp^2 = .073.

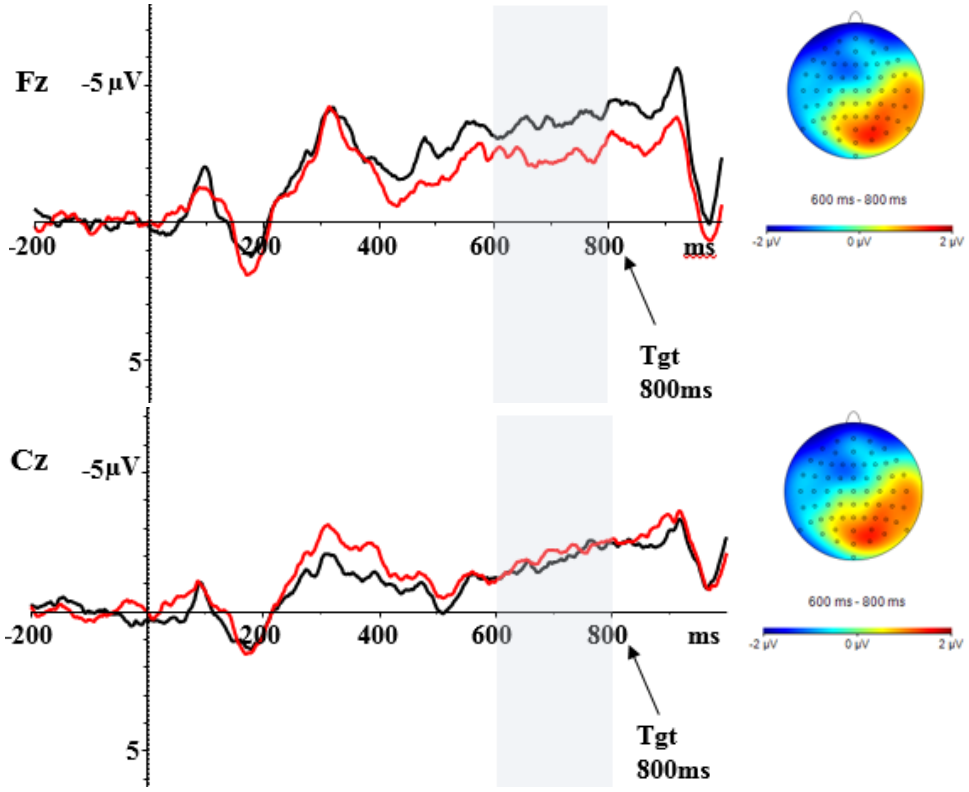


Fig. 9 Grand-averaged waveforms (n = 11) for valid trials (black ERP) and invalid trials (red ERP) in instructed attention condition at two electrode sites Fz and Cz. Vertical lines represent cue onset time preceded by 200 ms baseline and followed by 600 ms post-stimulus period. Target was presented at 800 ms. This figure includes topographical maps of the difference waves at each electrode and for 600–800 ms time interval.

To test the effect of trial validity (Hypothesis 4.d), mean amplitudes were subjected to the 2 x 2 x 2 repeated measure ANOVA with Cue Type (willed, instructed), Expected Cue Length (short, long) and Electrode (Fz, Cz) as factors. This analysis only included trials with Target type short (see Fig. 9 and Fig. 10 for details). There was no main effect of Cue Type, p = .059, ηp^2 = .312, no main effect of Expected Cue Length, p = .322, ηp^2 = .098, no main effect of Electrode, p = .612, ηp^2 = .027. Furthermore, Cue Type x Expected Cue Length, p = .457, ηp^2 = .057 and Cue Type x Electrode, p = .082, ηp^2 = .237 interactions were not significant. However, Expected Cue Length x Electrode interaction was significant, p = .041, ηp^2 = .356.

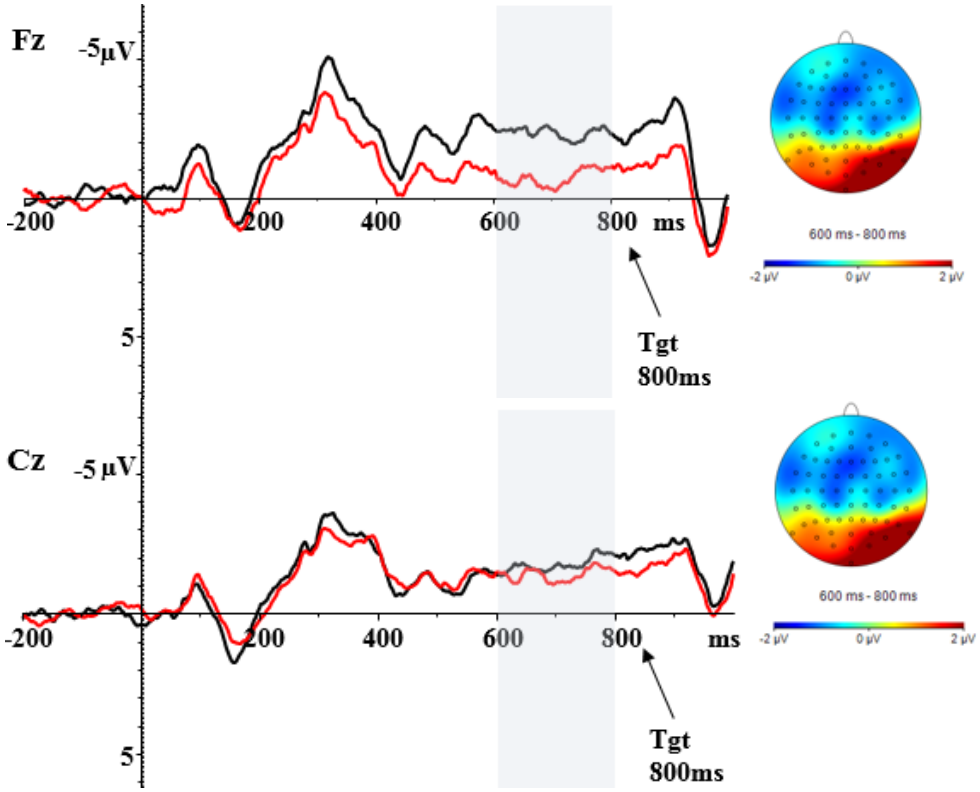


Fig. 10 Grand-averaged waveforms (n = 11) for valid trials (black ERP) and invalid trials (red ERP) in willed attention condition at two electrode sites Fz and Cz. Vertical lines represent cue onset time preceded by 200 ms baseline and followed by 600 ms post-stimulus period. Target was presented at 800 ms. This figure includes topographical maps of the difference waves at each electrode and for 600–800 ms time interval.

To further analyse the Expected Cue Length x Electrode interaction amplitude changes were subjected to the 2 x 2 repeated measure ANOVA with Cue Type (willed, instructed) and Expected Cue Length (short, long) as factors. Separate analyses were conducted for each electrode. For the Fz electrode there was a significant main effect of Cue Type, p = .009, F(1, 10) = 10.45, ηp^2 = .511 indicating that the amplitude values were more negative in the instructed attention condition. Furthermore, there was no main effect Expected Cue Length, p = .066, ηp^2 = .298 and no Cue Type x Expected Cue Length interaction, p = .403, ηp^2 = .071. For the Cz electrode there was no main effect of Cue Type, p = .498, ηp^2 = .047, no main effect of Expected Cue Length, p = .814, ηp^2 = .006, and no significant Cue Type x Expected Cue Length interaction, p = .845, ηp^2 = .004.

3.3 Time-frequency analysis

The analysis of theta activity was cue-locked and compared willed vs instructed attention. The analysis was separated for Expected Cue Length short and long. No differences in amplitude between the comparisons were observed in the current study (see Fig. 13 for details).

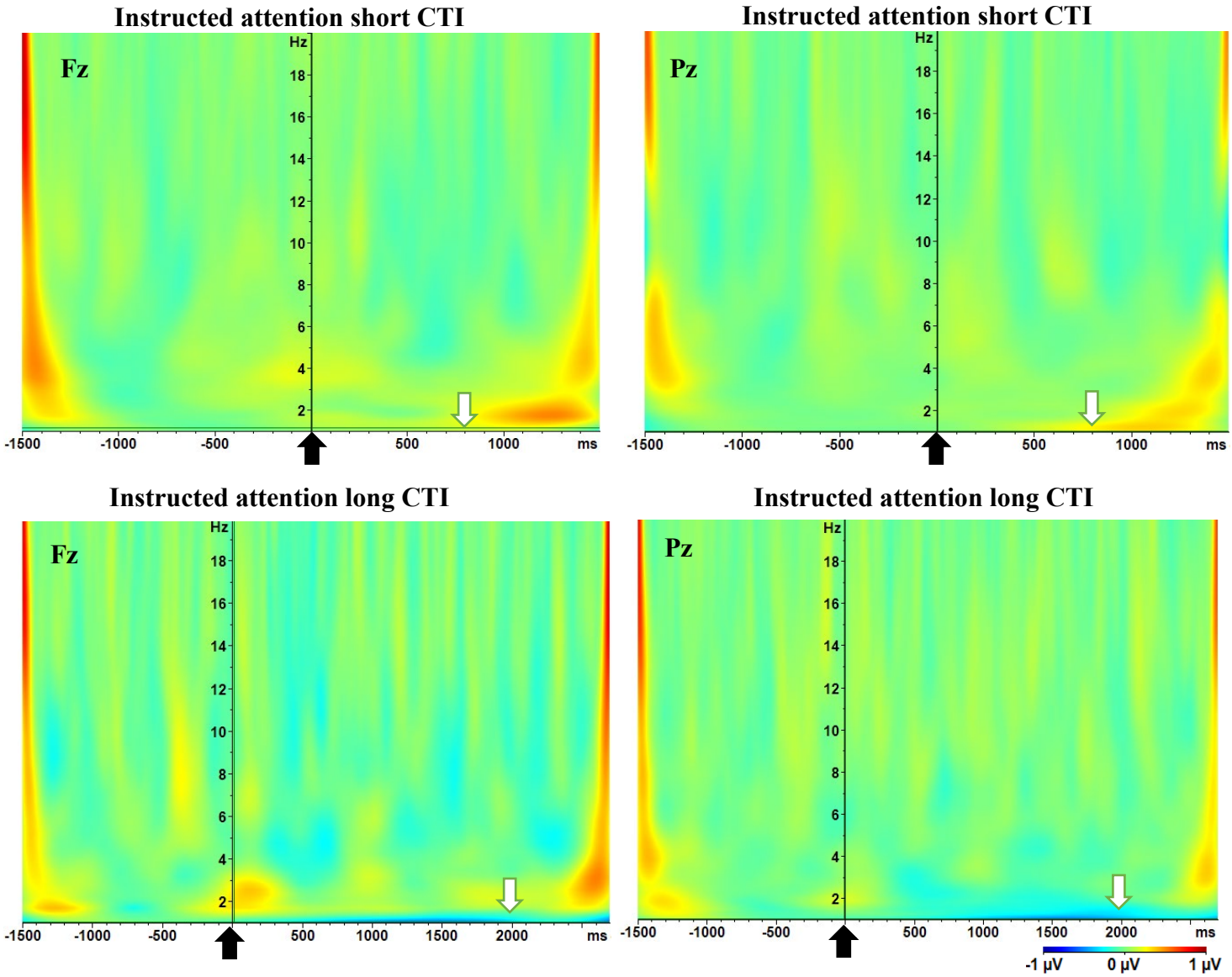


Fig. 11 Grand-averaged frequency spectrum for instructed attention (n = 11) encompassing baseline beginning at -1500 ms to cue onset (black arrow) at 0 ms and then to target onset (white arrow) at 800 ms in the short CTI and 2000 ms in the long CTI. The colour reflects amplitude (µV) as a function of time, x-axis. Frequency is on the y-axis. Data were baseline corrected from -1150 ms to -350 ms before stimulus onset. No specific region within the cue-target interval was chosen for analysis.

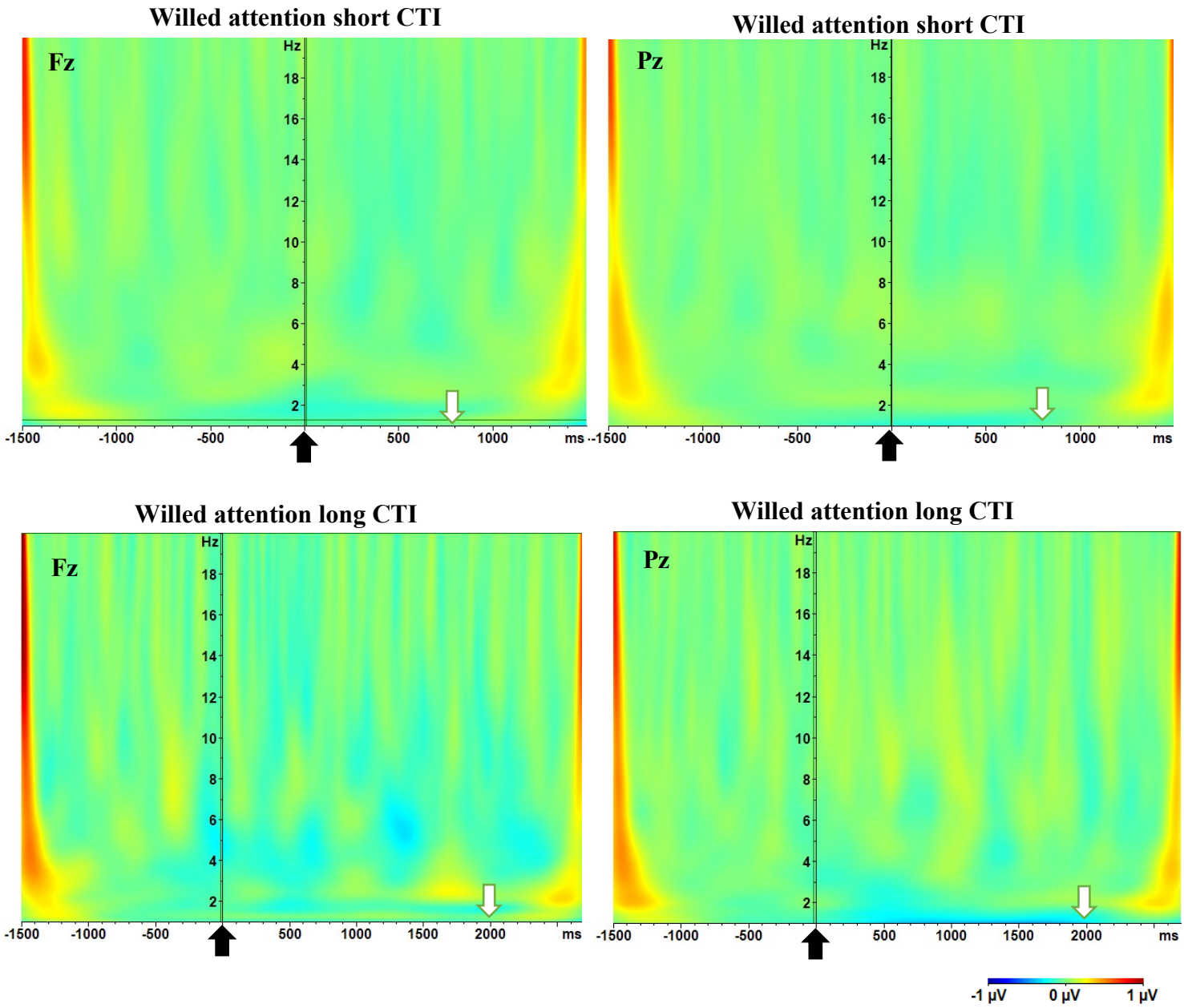


Fig. 12 Grand-averaged frequency spectrum for willed attention (n = 11) encompassing baseline beginning at -1500 ms to cue onset (black arrow) at 0ms and then to target onset (white arrow) at 800 ms in the short CTI and 2000 ms in the long CTI. The colour reflects amplitude (µV) as a function of time, x-axis. Frequency is on the y-axis. Data were baseline corrected from -1150 ms to -350 ms before stimulus onset. No specific region within the cue-target interval was chosen for analysis.

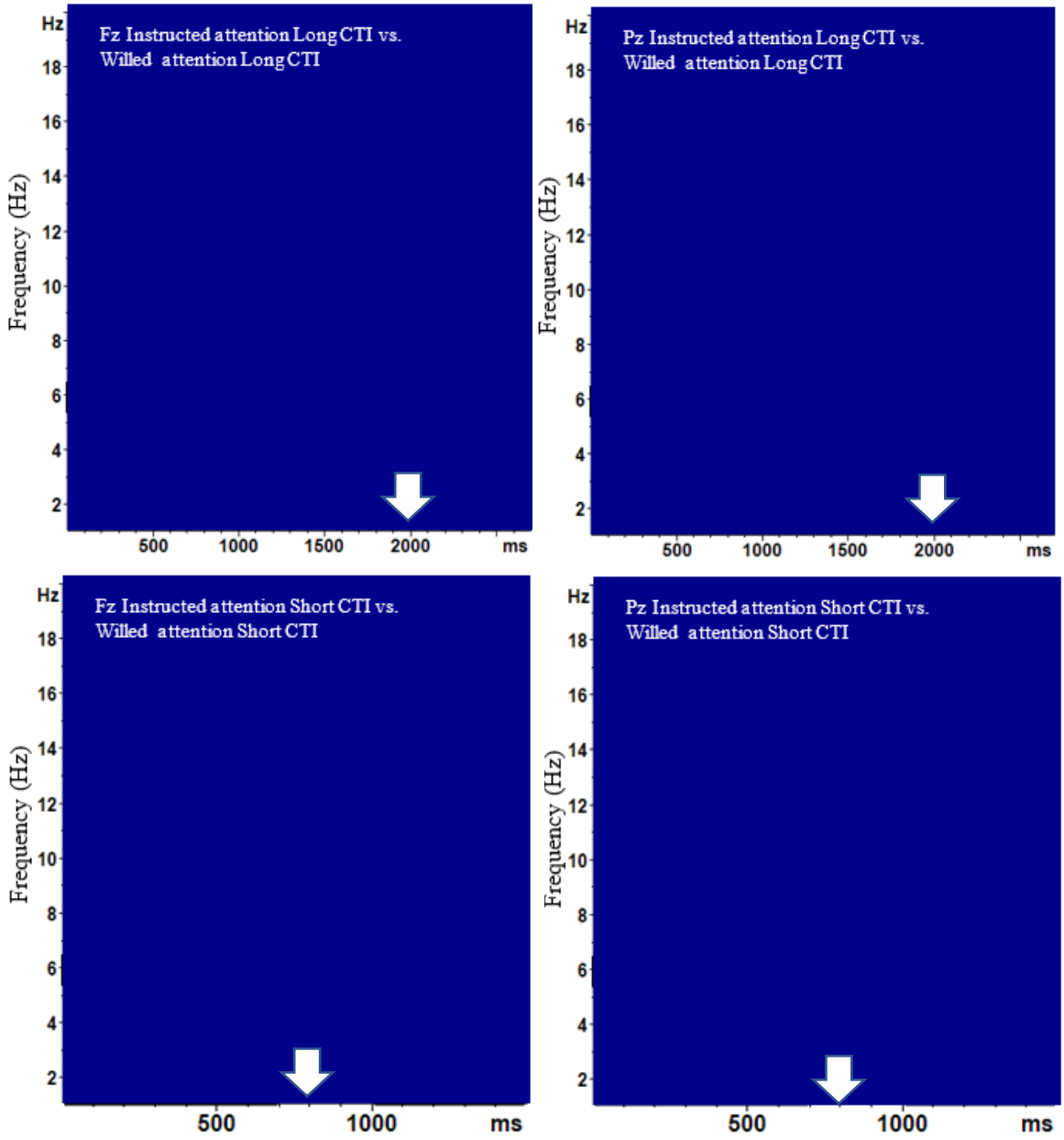


Fig. 13 False Discovery Rate (FDR) corrected contrasts between the conditions at Fz and Pz. The yellow colour was assigned to significant differences (pFDR <.05) whereas blue colour was assigned to non-significant differences. The x-axis is time (in millisecond) starting at cue onset. The white arrow corresponds to the target onset. Y-axis is the frequency (in Hertz).

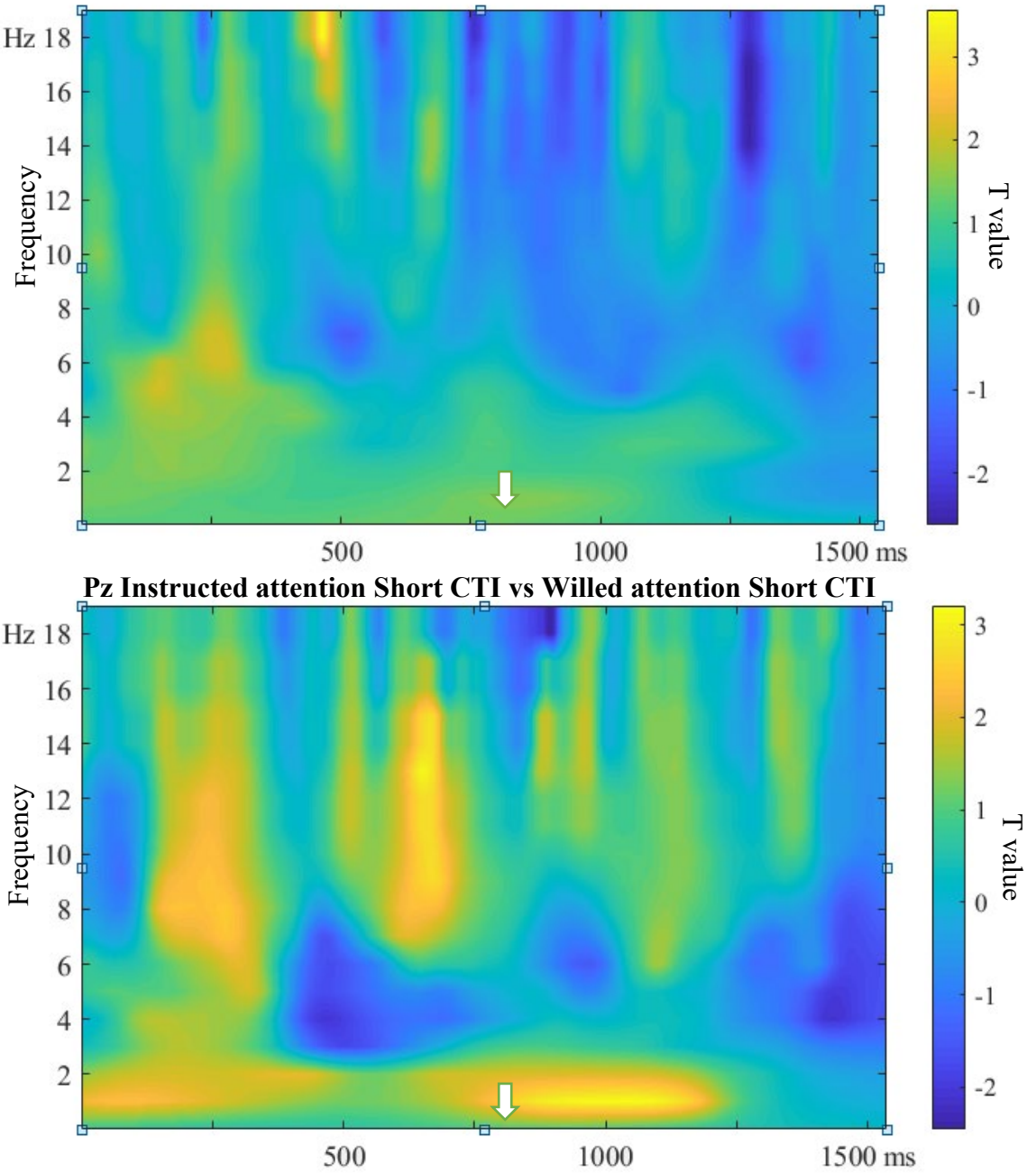


Fig. 14 Uncorrected t-values contrasts between Willed and Instructed attention at Fz and Pz electrodes. The x-axis is time (in millisecond) starting at cue onset. The white arrow corresponds to the target onset. Y-axis is the frequency (in Hertz).

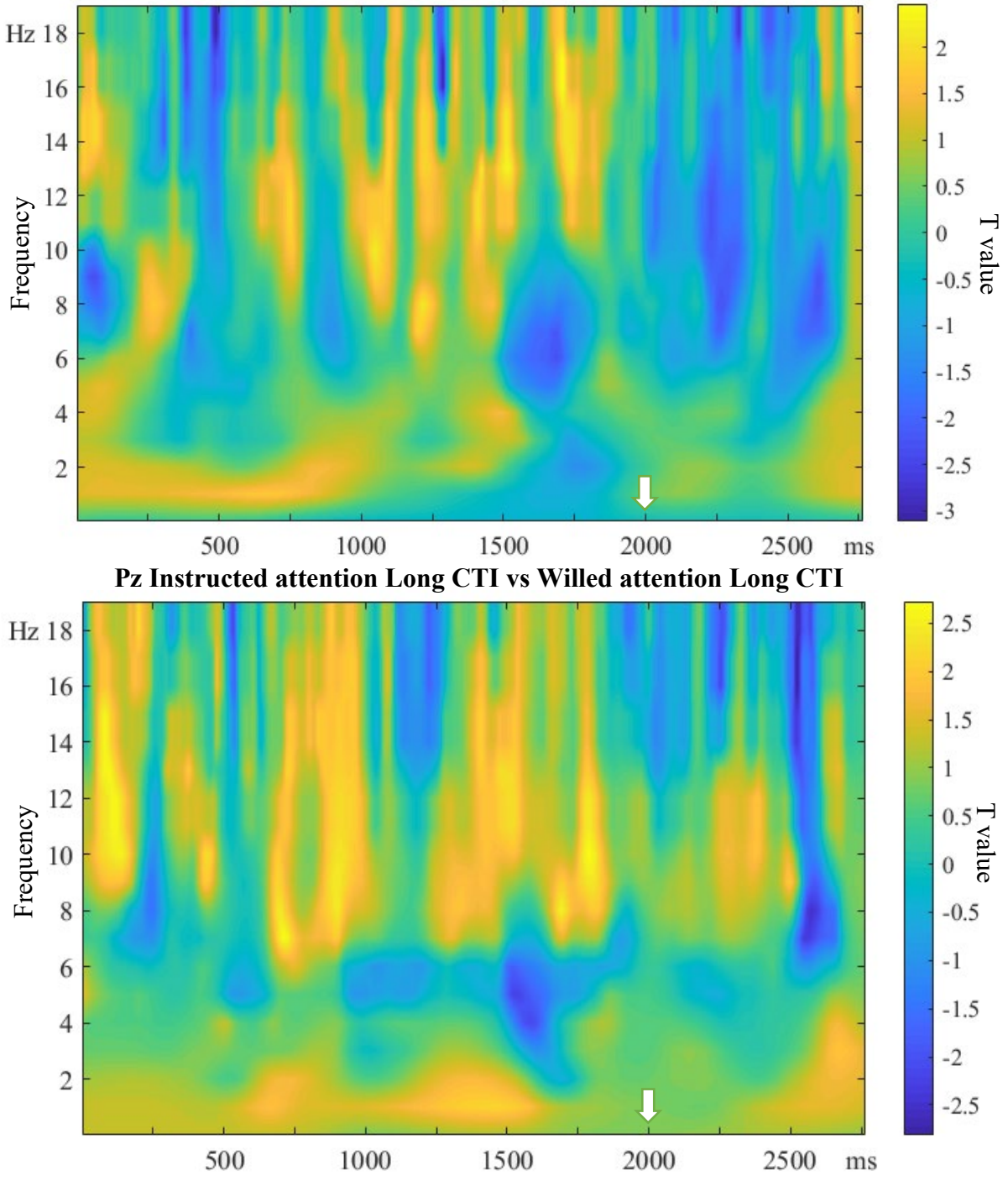


Fig. 14 Uncorrected t-values contrasts between Willed and Instructed attention at Fz and Pz electrodes. The x-axis is time (in millisecond) starting at cue onset. The white arrow corresponds to the target onset. Y-axis is the frequency (in Hertz).

4. Discussion

The current study aimed to develop the scope of the classic cueing paradigm. It incorporated a novel type of trial where the participants were required to decide for themselves whether to orient their attention towards the end of a short or long interval. The paradigm was based on the spatial attention task (Posner, 1980; Rajan et al., 2018) and it allowed us to explore how voluntary attention is initiated and controlled when no direct instructions are given. It is hard to draw concrete conclusions from the collected data as null results are difficult to interpret because they do not strictly mean no difference between groups. They can also mean that the data is insufficiently robust or there is insufficient power. Despite the small sample size some meaningful comments can be made on the findings. In the experiment, the participants were instructed not to respond to the unattended targets. Instead, they were asked to focus their attention selectively on a single time point. Consequently, it was not possible to demonstrate the improved responding to the cued targets compared to the uncued targets and to see whether this effect differed as a function of attention type.

In the present research, RTs to cued targets in willed and instructed attention conditions were compared. The exact direction of the difference was not predicted in the hypotheses. However, it was expected that RTs would be faster at both short and long interval in either instructed or willed attention condition. Contrary to my prediction, there were no differences in RTs between these attention types suggesting that the participants' attention level was approximately equated between conditions. In a related study (Lau, Rogers, Ramnani, Passingham, & Lau, 2004) on willed action participants' RTs were slower in the condition where they needed to make a choice. Participants were instructed to move a cursor over a specific target or, alternatively, they could choose a target themselves. Furthermore, in Taylor et al. (2008) study the participants made significantly more errors when they were required to decide where to orient their attention. Taylor et al. (2008) suggested that their participants may

not have yet successfully oriented their attention to one of two spatial locations before the target presentation. These studies suggest that willed temporal attention might be associated with increased cognitive effort leading to the deterioration of performance on the RT task. Therefore, it is possible that the lack of differences in RTs observed in the experiment reflects the limitations of the study pertaining to the small sample size.

RTs to the cued target presented at both short and long interval were also compared in the experiment. RTs follow the hazard function which indicates that the probability of an event occurring increases with the passage of time if it has not yet occurred (Correa et al., 2006; Cravo et al., 2011; Janssen & Shadlen 2005). The hazard function's influence on behaviour can be seen in a situation where a driver is waiting for a streetlight to become green. The probability of this happening increases with time and, based on this knowledge, a driver's preparation also increases facilitating a faster response. This expectation is continuously and automatically updated leading to RTs for targets at a long interval to be faster in comparison to targets at a short interval (Jones, 2019). Therefore, it was predicted that RTs to cued targets in the short CTI would be slower compared with RTs to cued targets in the long CTI. Contrary to this prediction, the experiment revealed no differences in RTs to targets presented at these two intervals in both willed and instructed attention conditions. The hazard function was found to influence behaviour even in the studies with comparably small sample size (Bueti, Bahrami, Walsh, & Rees, 2010; Cravo et al., 2011). Therefore, this lack of differences between RTs may not be related to the limitations of this study. Instead, these results could be caused by the high proportion of catch trials. Correa, Lupiáñez, Milliken and Tudela, (2004) and Correa et al. (2006) noted that introducing catch trials to the experiment resulted in increments in RTs for stimuli presented at the long interval and it led to the recording of the validity effect for the long CTI. Correa et al. (2006) suggested that the addition of catch trials to an experiment might cause what they called dispreparation which minimises the rate of anticipatory responses.

However, in the current study, it is difficult to assess whether a high proportion of catch trials caused dispreparation as no responses were recorded to uncued targets. Additionally, the cues used in the experiment did not provide certainty to the participants with regards to target onset time. Therefore, the participants were not incentivised to orient their attention towards a cued time point which could lead to the less pronounced bias towards that moment resulting in a lack of differences in RTs.

A crucial question in temporal attention research is whether early sensory or later decision and motor response stages of target processing are responsible for faster responding to valid targets (Nobre & Rohenkohl, 2014). In the present study, it was predicted that P1 and N1 amplitudes would be different for valid and invalid targets. This analysis was limited to a short CTI. Contrary to the prediction, the comparison of P1 and N1 revealed no differences between valid and invalid targets in both willed and instructed attention conditions. Speculatively, however, Figure 5 suggests that there might be a difference in the instructed attention condition that could potentially become significant with more power.

The previous visual-temporal attention studies did not provide an unequivocal answer to the question of whether temporal orienting influences perception. Some research did not report the modulation of perceptual processing by temporal attention (Griffin et al., 2002, Experiment 2; Miniussi et al., 1999). In contrast, there is evidence that temporal attention is associated with the modulation of N1 (Griffin et al., 2002, Experiment1). Correa and colleagues (2006) demonstrated the effect of temporal attention on P1. Further evidence supporting the influence of temporal attention on perceptual processing comes from studies using auditory stimuli. These repeatedly recorded modulation of N1 for cued targets in contrast to uncued targets (Lange & Röder, 2010). Furthermore, in the auditory temporal orienting studies the participants' attention was selectively oriented towards a single time point as only cued stimuli required a response. Conversely, in the visual-temporal attention research, typically, both

attended and unattended targets required a response. Thus, the participants' attention was divided between the potential moments of targets presentation (Nobre, 2001). Lampar and Lange (2011) using auditory temporal orienting task addressed this discrepancy in their two experiments. In Experiment 1 uncued stimuli were response relevant whereas in Experiment 2 only cued stimuli required a response. Thus, the task used in the second experiment could result in a more pronounced bias towards the cued moment. In contrast, the paradigm used in the first experiment could lead to uneven distribution of attentional resources over different moments in time. The enhanced target locked N1 was recorded only in Experiment 2. Lampar and Lange (2011) suggested that this discrepancy might be caused by the difference in the attentional resources allocation on cued time point in Experiment 2 compared to Experiment 1. It indicates that temporal attention can modulate early perceptual processing when attention can be selectively focused on a single time point. Seen in that light, if the difference between attended and unattended targets in the instructed attention condition in the N1 time range was significant it could be supportive of Lampar and Lange (2011) suggestion. It is important to remember that this speculative interpretation. Furthermore, the difficulty of target perceptual processing was previously suggested to be associated with early sensory-related ERP modulations in temporal attention research (Correa et al., 2006). However, in the current study, a simple detection task was used with all stimuli presented centrally. Thus, it is unlikely that the difficulty of perceptual processing would contribute to the potential difference.

It was also expected that P1 and N1 would differ between both types of attention. Willed attention engages additional cognitive processes related to decision-making which could result in differences in attentional focus level. For example, willed attention could be associated with an increase in cognitive effort that could interfere with attentional orienting. Previous studies indicated that, in a task where a cognitive effort level is manipulated, trials inducing high cognitive load are associated with decreased target stimuli processing as

indicated by slower RTs compared to trials with low cognitive load (Lavie, 2005; Lavie, 2010; Lavie, Hirst, De Fockert, & Viding, 2004). Consequently, willed attention could be associated with decreased perceptual processing of the target. Potentially, it could be reflected in the attenuation of P1 and N1 in a similar way as uncued targets are associated with decreased perceptual ERPs (Correa et al., 2006; Lampar & Lange, 2011). Alternatively, additional cognitive processes engaged by willed attention could be associated with an increase in attentional focus. Past research demonstrated that engaging more attentional resources by increasing perceptual load of the target stimuli is associated with decreased RTs to targets compared to trials with the low perceptual load (Handy, Soltani, & Mangun, 2001; Lavie, 2005). Therefore, an increase in attentional focus as a result of willed attention could be associated with the enhancement of perceptual processing. It could potentially be reflected in the enhancement of P1 and N1 in a similar way as cued targets are associated with larger perceptual ERPs (Correa et al., 2006; Lampar & Lange, 2011). However, in the current study, no differences in P1 and N1 between willed and instructed attention were recorded.

It was, also, expected that willed and instructed attention would have a different effect on CNV in the time interval directly preceding the target onset. From viewing Figure 7, it appears that there might be a difference between these two conditions; however, it is not significant, and it has diffused scalp distribution. However, the analyses demonstrated the medium effect size in the short CTI. Among the processes that were demonstrated to contribute to the CNV are stimulus anticipatory activity and motor response preparation (Mento, 2017). Therefore, a significant difference in CNV between willed and instructed attention could suggest that anticipation and response preparation could differ as a function of attention type. Similarly, to the potential modulation of perception, this difference could be dependent on the attentional focus level. In the long CTI, this comparison was highly non-significant. In the

present study, it was also expected that CNV would differ between cued and uncued target. This validity effect was not observed in the analysis.

Following the visual inspection of the CNV, mean amplitudes for 350 – 450 ms time interval in the short CTI in both willed and instructed attention were extracted and analysed (see Figure 7 for details). This approach was similar to Bengson et al. (2015) analyses who compared ERPs of willed and instructed visual-spatial attention recorded in the CTI also using Fz and Cz electrodes. In the present study, no differences between both attention types were found in the selected time range. However, this analysis demonstrated a medium/large effect size with posterior scalp distribution. Bengson et al. (2015) found differences between the attention types in two distinct time ranges. The first interval where the ERPs differed spanned from 250 to 350 ms post cue onset. The researchers suggested that this component reflects stimuli categorisation as a choice cue. It is unlikely that this component would reflect similar processes as an ERP in the present study. Firstly, I used blocked design, therefore, all cues in a block were either instructed or willed. As a result, the participants did not need to categorise stimuli as a choice cue on a trial by trial basis. Secondly, Bengson et al. (2015) recorded frontal scalp distribution whereas I observed posterior scalp distribution. The second time range where ERPs differed, in the discussed study, spanned from 400 to 800 ms post cue onset. The authors suggested that this component is related to decisional processes. This component was broadly distributed, and it had positive polarity in contrast to ERP recorded in the present study which had negative polarity and posterior scalp distribution. Therefore, the second component recorded in Bengson et al. (2015) study had distinct properties than the ERP recorded here suggesting that they might reflect different processes. Furthermore, mean amplitudes for 560 – 660 ms time interval were extracted in the long CTI in both willed and instructed attention. This analysis demonstrated highly non-significant results with a small effect size.

In the current study, it was predicted that theta power would be larger in willed compared to instructed attention condition. I took the data-driven approach; therefore, I did not make further predictions of when in the CTI this effect could be present. Contrary to my prediction, no significant differences were observed between willed and instructed attention in any region within the time-frequency matrix. However, a small decrease of the power in the theta frequency range can be observed in the long CTI (from 1300 to 1400 ms) at the Fz electrode in the willed attention condition (see Figure 11 for details). On willed attention trials, a cue induces a conflict between two potential time points that can be attended which is resolved by the decision-making. These cognitive processes are absent on the instructed attention trials. The theta frequency was demonstrated to be involved in conflict processing and decision-making (Cavanagh & Frank, 2014). Previous research has indicated that higher conflict situations are associated with higher theta activity (Cohen & Donner, 2013; Cohen & Ridderinkhof 2013; Rajan et al., 2018). These studies could support the interpretation that if theta activity was observed in the willed attention condition it could reflect conflict perception and decision-making processes. Stimulus locked theta is also associated with the novelty of a stimulus (Cavanagh & Frank, 2014). However, I used blocked design, thus, all stimuli in a block were either instructed or willed excluding the possibility of novelty influences on theta activity in the present paradigm.

In the experiment, any potential effect could be said to be reflective of task difficulty which could be exacerbated by using a blocked design. For example, the memorisation of decision made on the previous trial might be an inherent part of the performance on the willed attention task. Thus, it might be responsible for differences in the electrophysiological activity between willed and instructed attention. However, in the experiment, the participants were asked not to use any strategy when deciding to what time point to orient their attention. Furthermore, Taylor et al. (2008) included an additional memory block in their experiment to

test whether the choice related activity was different simply as a consequence of the memorisation of the previous decision. In that block, the participants were asked to remember each decision and to use that information when making a choice on a next trial. Taylor and colleagues (2008) found that choice related activity was not influenced by the processes related to the memory. Also, it is important to emphasise that choice cues were compared directly with instructed cues. Consequently, any potential differences would reflect all cognitive processes involved in orienting of both types of attention. Therefore, future research should use a variation of the current paradigm to isolate individual components of the willed temporal attention. Furthermore, future research should explore the functional significance of willed temporal attention by using a paradigm where both valid and invalid targets require a response.

4.1 Conclusions

In conclusion, the experiment revealed no differences in RTs and EEG recordings. However, a difference between willed and instructed attention in the CNV recorded in the time interval directly preceding the target in the short CTI showed a medium effect size. Furthermore, a comparison of the CNV recorded in the willed and instructed attention in the post cue time interval demonstrated medium effect size with posterior scalp distribution. It was only recorded in the short CTI. There, also, was a lateralised activity in the N1 time range in the instructed attention condition. Finally, a small decrease in the power of the theta activity was observed in the willed attention condition in the long CTI at the Fz electrode. These differences could potentially become significant with more power. Therefore, the interesting findings began to emerge that could aid researchers to characterise how voluntary attention is initiated and controlled when no direct instructions are given. It provides evidence that this approach is worth exploring and, in the future, someone should finish collecting the data. To the author's knowledge, this is the first study on electrophysiological correlates of willed

temporal attention. Furthermore, the current project demonstrates the feasibility of the paradigm used.

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Appendix A

Open Science Foundation Preregistration Documents

1. Study Information

1.1 Title

An EEG investigation into neural mechanisms of willed temporal attention

1.2 Description

The current project builds on a study by Rajan et al. (2018) who investigated neural correlates of volitional spatial attention. In their experiment, they used a Posner (1980) style cueing paradigm. However, their participants except being instructed where to expect a target stimulus also were asked to make a choice between two locations and expect target there. They called that condition willed spatial attention. Rajan et al. (2018) found an increase in frontal theta power (3 – 7 Hz) and enhanced frontal-parietal bidirectional interaction in willed attention condition as compared to instructed attention condition. These findings are in line with literature showing that low-frequency oscillations facilitate communication between distant brain regions (Cravo, Rohenkohl, Wyart, & Nobre, 2011; von Stein & Sarnthein, 2000). Bengson, Kelley, Zhang, Wang, and Mangun (2014) looked at the ERPs components of the same data set. It was the first exploration of ERP components of volitional spatial attention. They found a significant difference between choice-guided attention and instruction-guided attention of early positive ERP component with a frontal topographic distribution occurring between 250 ms and 350 ms after the cue. The power of that component was greater in willed attention condition. They, also, found a significant difference of broadly distributed negative component starting at 400 ms post cue and ending at 800 ms post cue. These results suggest that how orienting of spatial attention is modulated is different between endogenous and exogenous attention. However, what is unknown is whether and how willed temporal attention affects behaviour and whether this is different from instructed temporal attention. The current project addresses this question by looking at both behavioural data as well as EEG (see Study Information - Hypothesis for details).

1.3 Hypotheses

IV1 - Cue Type (instructed, willed)

IV2 - Expected Cue Length (short, long)

IV3 - Target (short, long)

DVs - RTs + Amplitude RTs

1. We expect to see the main effect of the Target such that RTs to long cue-target intervals should be faster than those to short cue-target intervals.

2. We expect to see the main effect of Cue Type – that reaction times will differ between instructed and willed conditions. Willed attention condition requires additional cognitive effort associated with the decision-making process. Thus, it is possible that willed attention condition will be associated with longer response times. Alternatively, willed attention decisions may result in an increased attentional focus leading to faster responses to willed compared to instructed cues.

3. We expect 2 x 2 interaction between Cue Type and Target. The possible increased amount of time that decision processing takes or the increase in attentional focus as a result of willed attention will likely result in response times being different for willed and instructed attention when the Target is long compared to short.

ERPs

ERPs include: CNV, P1, N1

4.a We expect to see the main effect of the Expected Cue Length such that ERPs will be different when the Expected Cue Length is short compared to long. This analysis is limited to when Target matches expected cue length (i.e. not invalid trials).

4.b We expect to see the main effect of the Cue Type – that ERPs will be different for willed vs instructed attention. This analysis includes Target type short and long, but only when Expected cue length matches (i.e. not invalid trials).

4.c We expect 2 x 2 interaction between Cue Type and Expected Cue Length such that ERPs for willed and instructed attention will differ when Expected Cue Length is short compared to long. This analysis includes Target type short and long, but only when Expected Cue Length matches (i.e. not invalid trials).

4.d We expect a 2x2 interaction between Expected Cue Length and Target. This analysis only includes trials with short Target. That is, a difference in ERPs for willed and instructed attention when Target is short and Expected Cue Length is short (valid), compared to when Expected Cue Length is long, but the Target type is short (invalid).

5. The analysis of theta oscillations will be cue-locked and compare willed vs instructed attention separately. The analysis will be separated for Expected Cue Length short and long. We expect Theta power to be larger in willed compared to instructed Cue Type. However, we take the data-driven approach; therefore, we do not make further predictions of when in the cue-target interval this effect will be present.

2. Design Plan

2.1 Study type

Experiment - A researcher randomly assigns treatments to study subjects; this includes field or lab experiments. This is also known as an intervention experiment and includes randomized controlled trials.

2.2 Blinding

No blinding is involved in this study.

2.3 Is there any additional blinding in this study?

The participants will not be aware of the study purpose.

2.4 Study design

Participants

The experimental protocol was approved by the Middlesex University Research Ethics Committee. Participants will need to be 18 years old or older and understand basic English to the degree that they can follow instructions. Both right and left-handed people with normal or corrected vision will be accepted for participation in the current study. Data from participants: 1) whose performance falls below the threshold (70% accuracy); 2) who are unable to adhere to the instructions; 3) with the excessive body or eye movements related artefacts will be excluded from the analysis. Trials with a response time faster than 100 ms or greater than 2.5 standard deviation away from a participant's mean will be rejected. Participants will be rewarded with either 15 pounds Amazon vouchers or course credit points.

Stimuli and task

Participants will be seated approximately 60 cm in front of a monitor. E-Prime 3 will be used to control the experiment (Spapé, Verdonschot, Dantzig, & van Steenbergen, 2014). Task used in the current study is a temporal analog of the spatial orienting of attention task (Posner, 1980; Rajan et al., 2018). In the instructed attention condition each trial will begin with one of two cues flashed on a screen for 200 ms. They will direct participants' attention to either Target short or Target long onset time. Both Target short and Target long will be a checkerboard flashed on the screen for 100 ms. The Target short will appear after 800 ms and Target long after 2000 ms (relative to the cue onset time). In willed attention condition, one cue will be flashed on the screen for 200 ms. It will direct participants to choose to attend to either Target short or Target long onset time. Participants' task will be to respond vocally as quickly and as accurately as possible to a Target. All stimuli will appear in the centre of the screen. Participants will be asked to focus 100% of their attention on the cued or chosen Target onset time and respond to the Target only if it appears after the attended time. Thus, there should be a minimal spread of attention towards the unattended delay. We will also intermix catch trials with the rest of the cues. Thus, on some of the trials, the Target will not be displayed. At the end of each trial, participants will be asked to report which time interval they attended to by pressing one of two buttons on a standard keyboard, using their dominant hand. The next cue will appear after a random inter-trial interval, ranging from 2000 ms to 3000 ms.

There will be 528 trials in the main experiment separated into 8 blocks each containing 66 trials. Willed and instructed attention trials will be separated into individual blocks. Both willed and instructed attention condition will comprise of 4 blocks. They will be presented in alternating order. Each block in the experiment will have 22 catch trials. In willed and instructed attention conditions, the Target short and Target long will be presented with equal probability. Cues will be valid 50% of the time in the instructed attention condition. The meaning of the cues and the order of blocks presentation will be counterbalanced across participants. Example cue mapping is available in the attachment.

During the experiment, the number of correct responses to valid willed attention cues will be counted. The validity of the willed attention cues will be determined using a participant's report. If this number is lower than 40 in either Target short or Target long condition, then a participant will take part in an extra block of willed attention trials. The experiment will take approximately 1.5h to complete. Prior to the recording, participants will complete 24 practice trials. At the end of each block, feedback will be provided containing a participant's average response time, number of errors, and the number of correct responses in that block. Participants will also be asked if they want to take a short break.

EEG recording

EEG will be recorded from 64 scalp electrodes using Biosemi with a sample rate of 2048 Hz.

2.5 Randomization

The current study will entail the within-subject design and trail order will be randomised.

3. Sampling Plan

3.1 Existing Data

Registration prior to the creation of data

3.2 Data collection procedures

Participants will be recruited via opportunity sampling, consisting of students (current Middlesex University students) and people from the general population. Participants will be recruited via word of mouth and an advert of the study on Middlesex University's Psychology Participation Portal (SONA system). Participants will be rewarded for their participation with either 15 pounds Amazon vouchers or course credit points. Participants need to be over the age of 18 years, have normal to corrected vision and a basic understanding of the English language to participate. Data will be collected from the end of February until the end of June 2020. The analyses will be done as soon as data collection finished. We specify exact exclusion criteria in the Analysis Plan section under Data Exclusion.

3.3 Sample size

Our target sample size is 46 participants.

3.4 Sample size rationale

An a priori power analysis (G*Power) was conducted to estimate the required sample size using small-to-medium effect size (f = 0.175) for a 2x2x2 interaction (based on the ERPs) with power at 95%. A moderate correlation between measures was assumed (r = .5). No sphericity correction was applied as no factor had more than two levels. The power analysis resulted in a sample size of 46 with an actual power of 0.95.

3.5 Stopping rule

Data collection will stop once 46 usable participants will be collected. Therefore, the rejection criteria analysis will be performed before, and separately to, any analysis of effects.

4. Variables

4.1 Manipulated variables

The design is a 2x2x2 repeated measures design:

IV1 - Cue type (instructed, willed)

IV2 - Expected cue length (short, long)

IV3 - Target (short, long)

DV1 - RTs

DV2 -amplitude

We will also include catch trials where no target is presented. They will appear with equal probability to short and long targets.

4.2 Measured variables

We will look at response times, theta band activity (amplitude/power) as well as event-related potentials (amplitude).

5. Analysis Plan

5.1 Statistical models

IV1 - Cue Type (instructed, willed)

IV2 - Expected Cue Length (short, long)

IV3 - Target (short, long)

DVs - RTs + Amplitude

EEG pre-processing analysis

The continuous EEG data will be filtered with a 0.1 Hz high pass and 40 Hz low pass filter, as well as a 50 Hz notch. All EEG data processing will be performed using Brain Vision Analyser. Bad channels will be interpolated using topographical interpolation. Data will be referenced offline to a common average. Blinks will be identified and corrected using an ICA as well as by manual component inspection. Target locked ERPs investigating the N1 and P1 will be segmented into 400 ms intervals, 100 ms pre-stimulus onset and 300 ms post-stimulus onset. A 100ms pre-stimulus baseline correction will be used and artefact rejection will use a +-100uV threshold at all electrodes.

Analysis of the CNV will segment the data into 1200 ms and 2400 ms epochs for short and long conditions respectively which include the cue-target interval and 200 ms pre-cue and 200 ms post target onset. Data will be segmented separately for long and short Targets. Baseline correction will be conducted 200 ms pre-cue onset and artefact rejection will use a +-100uV threshold at all electrodes in the CTI (i.e. excluding post target interval). The CNV will be analysed by extracting the mean amplitude of 200 ms pre-Target interval at Fz and Cz electrodes (Cravo et al., 2011; Faugeras & Naccache, 2016).

P1 and N1

Early visual ERP components, P1 and N1, will be analysed at lateral occipital electrodes PO7/8 (Miniussi et al., 1999). For the P1 component, a peak will be defined by as the largest positive amplitude averaged at electrodes of interest and, across all conditions, between 60 and 140 ms (Miniussi et al., 1999). Mean amplitudes will then be extracted for each condition encompassing 20 ms either side of the P1 peak. For the N1 component, the peak will be defined as the greatest negativity, averaged at electrodes of interest and, across all conditions, between 100 and 200 ms (Miniussi et al., 1999). Mean amplitudes will then be for each condition encompassing 20 ms either side of the N1 peak.

Statistical analysis

We will do several repeated measures ANOVAs to test out predictions. The analyses are labelled and correspond to the predictions.

ANOVA 1: A 2 Cue Type (willed, instructed) x 2 Target (short, long) repeated measure ANOVA will be used to analyse RTs (Hypotheses 1-3).

For analyses 2 – 5, separate ANOVAs will be conducted for P1 and N1.

ANOVA 2: A 2 Expected Cue Length (short, long) x 2 Electrode (PO7, PO8) repeated measure ANOVA will test hypothesis 4a. This analysis is limited to when Target matches expected cue length (i.e. not invalid trials).

ANOVA 3: A 2 Cue Type (instructed, willed) x 2 Electrode (PO7, PO8) repeated measure ANOVA will test hypothesis 4b. This analysis includes Target type short and long, but only when Expected cue length matches (i.e. not invalid trials).

ANOVA 4: A 2x2x2 Cue Type (willed, instructed) x Expected Cue Length (short, long) x Electrode (PO7, PO8) will test the hypothesis 4c. This analysis includes Target type short and long, but only when Expected Cue Length matches.

ANOVA 5: A 2x2x2 Cue Type (willed, instructed) x Expected Cue Length (short, long) x Electrode (PO7, PO8) will test the hypothesis 4d. This analysis only includes trials with Target type short.

ANOVA 6: For CNV Cue type (instructed, willed) x Electrode (Fz, Cz), a separate analysis will be conducted for target short and long. We expect the Cue type to interact with an electrode and if so, a separate analysis will be conducted comparing willed and instructed attention for each electrode.

The analysis of theta oscillations will be cue-locked and compare willed vs instructed attention separately (Hypothesis 7). The analysis will be separated for Expected Cue Length short and long. Two epochs of 500 ms before and 800 ms after as well as 500 ms before and 2000 ms after cue stimuli presentation onset will be used to conduct time-frequency analysis. For Expected Cue Length short, all Target types (short, long) and catch trials will be included. For Expected Cue Length long, Target type long and catch trials will be included, but Target type short excluded in the analysis. The data from ITI will be used as a baseline. Time-frequency analysis of the EEG data will be based on Morlet wavelets. We will conduct multiple t-tests on the amplitude values for each sample in the time-frequency matrix. We will use False Discovery Rate correction to correct resulting p values. It will allow us to identify regions within a time-frequency matrix that differ significantly (Silas, Tipple & Jones, 2019).

5.2 Inference criteria

Significance level alpha will set at 0.05

5.3 Data exclusion

Data from participants whose performance fall below the threshold (70% accuracy) will be rejected from the analysis. Data will be trimmed to exclude any responses below 100 ms and 2.5 SD above each participant's mean RT (across all conditions). Participants' data will not be included if they miss 20% or more of targets or respond to 50% or more catch trials. Participants will be excluded if they do not have 25 usable trials, after exclusion analysis, in each condition. Epochs were voltage exceeded ± 50 μV will be discarded. Lastly, trials with excessive muscle or body movements and with excessive eye movements or blinks related artefact will be removed.

5.4 Exploratory analysis

We may conduct additional exploratory cue-locked ERPs analysis to test for the main effect of the Cue Type.

Appendix B
Instructions

Instructions

Your task is to respond to the target - a checkerboard  as quickly as possible by saying “pah”

The experiment has two tasks – Instructed delay & You choose a delay

Instructions

Task 1. – Instructed delay

In the Instructed delay task you will see one of two different shapes 

They will instruct you when to expect the target - a checkerboard 

When you see 

expect the target to appear after a long delay

When you see 

expect the target to appear after a short delay

Your task is to say “pah” when you spot the target at the correct delay

Press SPACEBAR when you are ready to continue.

Instructions

It is important that you only respond to the target  when it appears at the same delay you expected it to appear.

Example. A 

is shown which **<u>instructs you</u>** to expect the target  after a long delay and the target appears after a long delay, then **<u>say "pah"</u>**

Example. A 

is shown which **<u>instructs you</u>** to expect the target  after a long delay but the target appears after a short delay, then please **<u>do not respond</u>**

At the end, you will be asked to report whether you expected the target after a short (press 1) or long delay (press 2).

At times there **<u>will be no target at all</u>**, if it happens do not say "pah" – just wait until the next part of the experiment

Press SPACEBAR to see what short and long interval is

Now let's practice Task 1

Remember:

- Long Delay

- Short Delay

Press SPACEBAR when you are ready

to continue

Instructions

Task 2. You choose delay

In Task 2 you will see one shape C

When you see C choose to expect the target  after either a short or long delay

Your task is to say “pah” when you spot the target.

Press SPACEBAR when you are ready to continue.

Instructions

It is important that you only respond to the target  when it appears after the same delay you have chosen to expect it.

Example. A C is shown and you **choose** to expect the target after a short delay but the target appeared after a long delay, then please **do not respond** to a target.

Example. A C is shown and you **choose** to expect the target after a short delay and the target appeared after a short delay, then **say “pah”**.

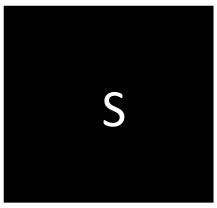
At the end, you will be asked to report whether you expected the target after a short (press 1) or long delay (press 2).

At times there **will be no target at all**, if it happens do not say “pah” – just wait until the next part of the experiment

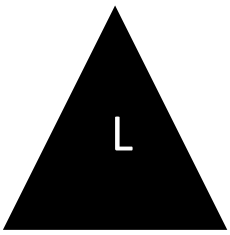
Press SPACEBAR when you are ready to practice Task2

Task 1

Remember:



- Short Delay



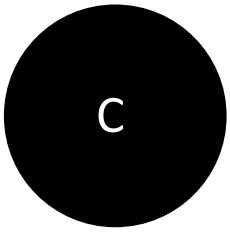
- Long Delay

Press SPACEBAR to start Task 1

Task 2

Remember:

You will see:



Make a choice

Press SPACEBAR to start

Task 2

Consent Form

Psychology Department
Middlesex University
Town Hall, The Burroughs, Hendon,
London NW4 4BT

Informed Consent

Middlesex University School of Science and Technology

Psychology Department

Written Informed Consent

Title of study: EEG and Temporal Attention (2019/2020)

Principal Investigators:

Dr A.Jones (A.J.Jones@mdx.ac.uk)

Dr J. Silas (J.E.Silas@mdx.ac.uk)

Please confirm that you have read and understood the above information and that you agree to participate in the current study by ticking the following items:

* I have understood the details of the research as explained to me by the researcher and confirm that I have consented to act as a participant.

* I have been given contact details for the researcher in the information sheet.

* I understand that my participation is entirely voluntary, the data collected during the research will not be identifiable.

* I understand that I can ask for my data to be withdrawn from the project by (1st of July 2020) without any obligation to explain my reasons for doing so.

* I further understand that the data I provide may be used for analysis and subsequent publication in journal articles or grant applications, and I provide my consent that this may occur

Name: Signature:

Participant Information Sheet

Psychology Department
Middlesex University
Town Hall, The Burroughs, Hendon,
London NW4 4BT

EEG and Temporal Attention (2019/2020)
Participant Information Sheet

Dear Participant,

You are being invited to take part in a research study. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what it will involve. Please read the following information carefully and ask if there is anything that you do not understand. Take time to decide whether or not you wish to take part.

All proposals for research using human participants are reviewed by an Ethics Committee before they can proceed. The Middlesex Psychology Research Ethics Committee has reviewed and approved this proposal (ID number XXX).

What is the purpose of the study?
The current study aims to investigate neural mechanisms involved in the modulation of the temporal attention. EEG (scalp surface electrical activity) will also be recorded as part of this study.

What will happen if I take part in this EEG study?
You will be asked to attend one session in a psychology laboratory at Middlesex University in Hendon NW4 4BT.

During this session you will complete a straightforward task on the computer. In this task you will be shown three shapes (circle, triangle, and rectangle). They will direct your attention to different points in time when you will be shown a target (checkerboard). Your task will be to recognise this target as quickly and accurately as possible, and when you do, to press a button on a keyboard.

While you will complete the computer tasks, we will record electroencephalography (EEG) from the scalp of your head. EEG records the small electrical activity your own brain produces using electrodes. You will wear an EEG cap which includes electrodes and electrodes will also be placed near your eyes to record eye movements and blinks. To get a good connection between the scalp and electrodes, each electrode will first be filled with a gel. This gel is specifically manufactured to be used for EEG testing such as this and is very unlikely to cause any irritation. However, it should not be used on damaged skin or if you have a history of skin

allergies. Specific details of the content of the gel are available and you can try a small amount of gel on your arm first if you wish to test what it feels like. This gel washes out very easily with warm water. Shower facilities, a towel to dry your hair, and a hairdryer will be provided so you can do this after the testing is finished. From start to finish the testing will take about 2 hours. This includes setting everything up and putting the electrodes on your head, and you washing your hair after.

If you would like more information about EEG and this study, then please do not hesitate to contact one of the researchers named below.

What will happen to the study results?
The responses we collect during the experiment will be used to advance understanding of the brain mechanisms involved in temporal attention. We may present the results at conferences and publish it in appropriate outlets (e.g., academic journals). If we do this, we present the average result from a group of participants. Your individual data will remain anonymous so that no one would be able to identify you from the data. Your responses on the computer task not be associated with your name and will be stored on a password locked computer in a secure office at Middlesex University. Your data will only be accessed by authorised members of the research team. Our procedures adhere to the General Data Protection Regulation. If you would like to receive a copy of any papers that are published as a result of this study, please let the experimenter know.

Do I have to take part?
No, your participation is voluntary, and you can withdraw from the study at any time without giving a reason. If you decide to take part, you will be asked to sign a consent form. Participants will be awarded a credit point (if applicable). There is no penalty if you decide that you do not wish to take part, and you may withdraw your participation at any point during the experiment without having to give a reason. If you decide afterwards that you would like to withdraw your data, then you may do so up until the point at which data analysis begins (1st of July 2020). Please contact the principle investigator to make this request.

Who has reviewed the study and who will collect the data?
All proposals for research using human participants are reviewed by an Ethics Committee before they can proceed. The Middlesex Psychology Department's Research Ethics Committee have approved this proposal.
Your information shall be collected by a member of the research team led by Principle Investigators Dr Alexander Jones and Dr Jon Silas. The data is kept confidential and shall be stored anonymously in a password locked computer. The study may be published but confidentiality will be respected, therefore your identity will not be revealed.

Are there any other requirements?
Because images will be flashed on the screen throughout the experiment, participants with photosensitive epilepsy should not take part in this study. Additionally, participants should have normal or corrected vision and be fluent in English language.

Principal Investigators:
Dr A.Jones (A.J.Jones@mdx.ac.uk)
Dr J. Silas (J.E.Silas@mdx.ac.uk)

If you have any complaints about this research please contact the Chairs of the Psychology Ethics Committee Dr N. Brunswick, n.brunswick@mdx.ac.uk and Dr L. Marzano, l.marzano@mdx.ac.uk

Debriefing

Psychology Department
Middlesex University
Town Hall, The Burroughs, Hendon,
London NW4 4BT

EEG and Temporal Attention (2019/2020)
Debriefing

Principal investigators: Dr Alexander Jones (a.j.jones@mdx.ac.uk) and Dr Jon Silas (j.e.silas@mdx.ac.uk)
Experimenter: Maciej Malinowski (mm2851@live.mdx.ac.uk)

Thank you very much for your participation in this research, we greatly appreciate your contribution.

This study aims to further understand the differences between neural correlates of spatial and temporal attention. It builds on the Rajan, Siegel, Liu, Bengson, Mangun, and Ding (2018) study. They found an increase in the frontal theta power for a choice cue as well as an increase in frontal-parietal theta-band coherence. Their results suggest that theta oscillations index the decision-making process in the frontal cortex. In the current study, we replicated Rajan et al. (2018) study for temporal attention.

If you have any serious concerns about the ethical conduct of this study, please inform the Chair of the Psychology Research Ethics Panel (Psy.Ethics@mdx.ac.uk) in writing, providing a detailed account of your concern. If you have any queries about this research or would like to ask any further questions, please contact the experimenter (mm2851@live.mdx.ac.uk). If you would like to withdraw your data, please email the experimenter or a principal investigator. You can withdraw your data any time before data analysis begins on the 1st of July 2020.

Once again, we would like to thank you for your valuable contribution to this research.