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Investigating the Relationship Between N2pc and Rapid Saccadic Eye Movements

A thesis submitted in partial fulfillment of the requirement
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by

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Introduction

Selective attention is a fundamental cognitive process that enables individuals to focus on specific stimuli or aspects of their environment while simultaneously ignoring irrelevant or distracting information. This ability to filter and prioritize sensory input plays a crucial role in human cognition by allowing for the efficient allocation of limited cognitive resources to the most relevant aspects of the environment, thereby facilitating goal-directed behavior and adaptation (James, 1890; Broadbent, 1958; Treisman, 1960; Desimone & Duncan, 1995)

Early theories of selective attention were proposed by William James (1890), who emphasized the importance of attention in the selective processing of perceptual information. Broadbent's (1958) filter model of attention provided a more structured framework, suggesting that attention acts as a filter that limits the processing of information based on its physical properties, such as location or modality. This concept was further refined by Treisman's (1960) attenuation theory, which posited that unattended stimuli are not entirely blocked but rather attenuated, allowing for some weakened degree of processing.

Selective attention has been extensively studied using various experimental paradigms, which have contributed to our understanding of the underlying neural mechanisms. One such paradigm, the dichotic listening task, was employed by Cherry (1953) to demonstrate that participants could selectively attend to one auditory stream while ignoring another (Cherry, 1953). This finding provided evidence for the existence of selective attention and laid the groundwork for subsequent research in the field.

Visual selective attention, the focus of the present paper, has been studied using a variety of experimental paradigms, including the spatial cueing task (Posner, 1980) and the visual search task (Treisman & Gelade, 1980). Posner's spatial cueing paradigm provided crucial insights into the mechanisms of attentional orienting and the involvement of both endogenous (voluntary) and exogenous (involuntary) processes in directing attention (Posner, 1980). Moreover, the visual search paradigm developed by Treisman and Gelade (1980) led to the influential feature integration theory, which proposed that attention is necessary for the binding of basic visual features into coherent objects (Treisman & Gelade, 1980).

Neurophysiological studies using event-related potentials (ERPs) have further elucidated the neural correlates of selective attention. One key ERP component, the N2pc, has been linked to the allocation of attention in visual search tasks (Luck & Hillyard, 1994). Another well-studied ERP component is the P300, which has been associated with higher-order cognitive processes, such as decision-making and target detection (Sutton et al., 1965; Polich, 2007).

Functional neuroimaging techniques, such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), have also provided valuable insights into the neural basis of selective attention (Corbetta et al., 1991; Kastner & Ungerleider, 2000). These studies have identified a distributed network of brain regions involved in attentional processing, including the frontoparietal network, which comprises the frontal eye field (FEF), intraparietal sulcus (IPS), and superior parietal lobule (SPL) (Corbetta & Shulman, 2002).

Taken together, the body of research investigating both the behavioral and neural correlates of attention has provided theoretical and empirical advances in the study of selective attention as well as valuable insights into its underlying neural mechanisms and the ways in which attention is allocated to process sensory information efficiently. With the application of advanced neuroimaging and electrophysiological techniques, the field of cognitive neuroscience continues to expand our understanding of the complex processes that underpin selective attention.

N2pc

As previously mentioned, the N2pc (N2-posterior-contralateral) is an event-related potential (ERP) component that has been widely investigated in the context of visual selective attention and visual search tasks. The N2pc is a negative-going deflection observed at posterior scalp sites contralateral to the attended or target stimulus, typically emerging around 200-300 ms after stimulus onset (Luck & Hillyard, 1994; Eimer, 1996). The N2pc has been considered a reliable neural marker of attentional deployment, reflecting the attentional selection of task-relevant visual information and the suppression of task-irrelevant distractors (Luck & Hillyard, 1994; Eimer, 1996; Woodman & Luck, 1999; Kiss et al., 2008).

The discovery of the N2pc component can be attributed to the seminal work of Luck and Hillyard (1994), who identified this contralateral negativity in a visual search task requiring participants to find a target stimulus among distractors. They demonstrated that the N2pc was selectively elicited by the target stimulus, with the amplitude of the component being modulated by the amount of focused attention deployed (Luck & Hillyard, 1994). This finding provided strong evidence for the role of the N2pc in the attentional selection of relevant visual information, as well as the filtering of distractors.

Subsequent research has further elucidated the functional significance of the N2pc in visual search tasks. Eimer (1996) demonstrated that the N2pc was also sensitive to the difficulty of the visual search task, with the latency of the component increases as the task became more challenging. This finding suggested that the N2pc not only reflects attentional selection processes but also indexes the time it takes to locate and select the target stimulus among distractors (Eimer, 1996).

The N2pc has also been linked to the lateralization of attention in the visual field, as it is observed contralateral to the attended hemifield (Luck et al., 1997; Hopf et al., 2004). This lateralization has been proposed to reflect the involvement of spatially specific attentional mechanisms that bias the processing of visual information in the attended hemifield (Luck et al., 1997). Moreover, the N2pc has been associated with the activation of the parietal cortex, which plays a crucial role in spatial attention and the allocation of attentional resources (Hopf et al., 2004; Seiss et al., 2009).

In addition to its role in the attentional selection, the N2pc has also been implicated in the suppression of task-irrelevant distractors. Woodman and Luck (1999) found that the N2pc was not only elicited by the target stimulus but also by salient distractors, suggesting that the component reflects the suppression of irrelevant stimuli that compete for attentional resources. This view is supported by the finding that the N2pc is larger in amplitude for distractors that are more similar to the target, indicating that the degree of attentional suppression is modulated by the similarity between target and distractor stimuli (Hickey et al., 2009; Töllner et al., 2011).

Recent research has also investigated the temporal dynamics of the N2pc, revealing that the component can be decomposed into earlier and later subcomponents (Eimer & Kiss, 2008; Jannati et al., 2013). The earlier subcomponent has been associated with the initial attentional capture by the target stimulus, while the later subcomponent is thought to reflect the sustained allocation of attention to the target and the concurrent suppression of distractors (Eimer & Kiss, 2008; Jannati et al., 2013). These temporal subdivisions of the N2pc provide further insight into the dynamic interplay between attentional selection and distractor suppression during visual search tasks.

The N2pc has also been employed in studies examining the impact of cognitive control on attentional selection. For instance, Eimer & Kiss (2010) demonstrated that the amplitude of the N2pc was modulated by the top-down control settings, with a larger N2pc observed when participants were actively searching for a specific target feature compared to when they were searching for any feature that deviated from the background. This finding highlights the influence of cognitive control on the allocation of attentional resources during visual search tasks and the utility of the N2pc in studying these processes (Eimer & Kiss, 2010).

In recent years, there has been growing interest in the N2pc as a tool for investigating various aspects of visual cognition, such as working memory, perceptual load, and individual differences in attentional capacity (Gaspelin et al., 2015; Mazza et al., 2007; Sawaki & Luck, 2010). These studies have underscored the versatility and sensitivity of the N2pc as an electrophysiological marker of attentional processes, making it an invaluable tool for cognitive neuroscience research.

In conclusion, the N2pc is a well-accepted index of visual selective attention and the deployment of attention in visual search tasks, providing crucial insights into the mechanisms underlying attentional selection, distractor suppression, and the influence of cognitive control on visual processing. The N2pc has also served as a versatile tool for exploring various aspects of visual cognition. Still, questions remain about the complex interplay between the N2pc and other behavioral indices of attentional selection in visual search such as the production of saccadic eye movements.

Covert Attention and Saccadic Eye Movements

While much research has been conducted on the N2pc component, few studies have examined its interplay with eye movements. In a recent paper, Talcott and colleagues investigated whether N2pc mandatorily precedes the onset of rapid saccades during visual search tasks that involve natural eye movements. The authors reported no significant N2pc signal prior to saccadic onset but identified a post-saccadic N2pc-like negativity (Talcott & Gaspelin, 2021).

During overt visual search, eye movements are typically used to take advantage of accurate and high-resolution foveal vision (Henderson, 2003). While covert attentional shifts can occur independently of overt eye movements (Kastner & Ungerleider, 2000; Posner, 1980; Woodman & Luck, 1999), it is widely assumed that covert attentional shifts guide overt visual searches. Specifically, it is believed that covert attention is directed to the target of the upcoming saccade and then guides the eyes to follow along. Indeed, the results of a number of studies using visual search tasks have supported this hypothesis, demonstrating that humans automatically deploy covert attention to the target of the upcoming saccade (Beauchamp et al., 2001; Deubel & Schneider, 1996).

Talcott and colleagues (2021) raised the question of whether N2pc components necessarily precede saccadic movements in visual search tasks, given the typical relationship between covert attentional shifts and eye movements. The authors pointed out that while some studies have reported a significant N2pc component prior to saccadic onset, the methods used in those studies were problematic. Specifically, these previous studies involved asking participants to refrain from making eye movements and instead use covert attention to identify the target before initiating the saccade (Luck et al., 1997; Woodman & Luck, 2003). The mean onset of saccadic movement in those studies was around 275-375 ms after stimulus onset, which Talcott et al., (2021) considered to be a delayed and unnatural response time. Previous studies have demonstrated that under natural conditions, where eye movements are generated freely in service of visual search, saccades can occur rapidly, at approximately 50-150 ms after stimulus onset

(Chelazzi et al., 1998; Horowitz et al., 2009). In fact, Talcott et al., (2021) found a mean first saccade onset time of around 200 ms after stimulus presentation, supporting the notion that previous studies had artificially prolonged saccade latency. Taken together, these studies raised questions about the temporal relationship between the N2pc and saccadic eye movements as well as the potential temporal variability introduced by task instructions.

N2pc and temporal variability

Dowdall et al. (2012) conducted a study investigating the effects of efficient and inefficient searching strategies on the amplitude of the N2pc component by introducing temporal jitter and variability in its latency (Dowdall et al., 2012). In their study, participants were presented with a pair of stimuli consisting of a complete circle (O-shape) and an incomplete circle (C-shape), as targets and distractors. Participants were instructed to search for either the O-shape or C-shape with covert attention (no eye movement). The results demonstrated that when the O-shape was the target (TODC), participants' reaction time (RT) increased significantly as the number of items in the search array increased, but that there was no significant increase in RT when the C-shape was the target of the search (TCDO). Dowdall et al., (2012) interpreted this result to mean that an “efficient” search strategy was used by participants in the TCDO condition but that an “inefficient” search strategy was employed in the TODC condition (Dowdall et al., 2012).

Interestingly, Dowdall et al. (2012) observed a significant N2pc component in efficient searches (TCDO condition), but failed to detect an N2pc component in inefficient searches (TODC condition), despite the elicitation of covert attentional shift. In order to better understand this difference between the TCDO and TODC conditions, they then gathered all trials into 10 groups based on RT, ranging from the fastest 10% to the slowest 10%, and calculated the N2pc in each group. They found that a significant N2pc component was observed in every group, but that there was considerable temporal variability in the N2pc component across groups, ranging from 200ms after stimulus onset to almost 400ms after stimulus onset. As a result, Dowdall et al. (2012) concluded that it is precisely this temporal jitter in the N2pc component that may have rendered it absent in the TODC condition when all trials were used in the average.

Present Study

The primary goal of the present study is to replicate and extend Talcott et al., (2021) and Dowdall et al.'s (2012) research to determine how the N2pc component is related to eye movement when saccades can be generated freely to aid visual searches.

The stimuli used by Talcott (2021) involved targets and distractors that consisted of conjunctions of two features (shape and color), which have been established to elicit serial, or what Dowdall et al., (2012) referred to as inefficient, search strategies (Treisman & Gelade, 1980). Thus, our approach will be to combine Talcott's (2021) manipulation of task instructions allowing or prohibiting eye movements with the "C" and "O" stimuli used by Dowdall et al., (2012). This unique combination will yield a design that varies in the type of attention deployed, namely covert (no eye movement allowed) or overt (eye movement allowed), and the number of items in the search display.

Additionally, this study aims to investigate the impact of temporal variability on the N2pc component during overt visual search tasks. Prior research has demonstrated that covert searches in the target-contingent display onset (TCDO) condition typically result in an efficient search strategy, eliciting a pronounced N2pc component. In contrast, overt searches are thought to induce an inefficient strategy. Earlier investigations have indicated that visual search tasks employing overt attention and utilizing high-resolution foveal vision tend to be sequential;

attention does not advance to the subsequent item until the processing of the current item is completed, as evidenced by a linear increase in reaction time as the number of items in the search array grows (Donk & van Zoest, 2008; Hooge & Erkelens, 1999; Olivers & Nieuwenhuis, 2005; Treisman & Gelade, 1980). Should a temporal relationship between N2pc and saccade onset exist, and assuming that overt searches are indeed inefficient, we would anticipate an attenuated amplitude when segmented electroencephalogram (EEG) data are time-locked to stimulus onset, while a significant negativity would be observed when time-locked to saccade onset.

Hypotheses

1. We expect that reaction time (RT) will increase significantly in the overt attention (eye movements allowed) condition as the number of items in the search array increases but that RT will not increase with the number of items in the search display when covert attention (no eye movements) is used.
2. We expect that the N2pc will be maximal in the covert attention condition.
3. We expect that when an inefficient search strategy is used in overt searches, the amplitude of the N2pc will decrease with the number of distracters in the search display.
4. We expect a significant correlation between the first saccade onset latency and N2pc or N2pc-like component latency.
5. We expect there exists a correlation between the amplitude of the N2pc or N2pc-like component and the onset latency of the first saccade.

Method

Participants

Thirty-two participants, consisting of 14 females and 18 males, aged between 18 and 22 years, were recruited from the College of William & Mary campus for this study. Informed consent was obtained from all participants, who were made aware that their data would be utilized for research purposes. Participants all self-reported normal or corrected-to-normal visual acuity and normal color vision.

Apparatus

All participants were seated in a dark, electrically-shielded room, with a 32-inch monitor positioned 100cm from their eyes. An Xbox Elite Wireless Series 2 controller was utilized as a response device, connected to the computer via a cable. Stimulus presentation was controlled and behavioral data were collected using custom software written in the Matlab programming language using Psyctoolbox3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). To minimize possible temporal variance caused by the monitor response time, the onset time of the visual stimuli was measured using a dedicated photo sensor.

Stimuli and procedure

The search task was based on Dowdallet al.'s (2012) study of temporal variability in N2pc. The stimuli are comprised of an incomplete circle (C-shape) as the target and a complete circle (O-shape) as the distractor, with each search item occupying 3° of visual angle and an equidistant placement from the central fixation cross. The gap in open circles is comprised of 1° of visual angle (approximately 1/5 of the circumference). Each trial featured a search array of two, four, or six items, arranged symmetrically on both the left/right and top/bottom axes (see Figure 1).

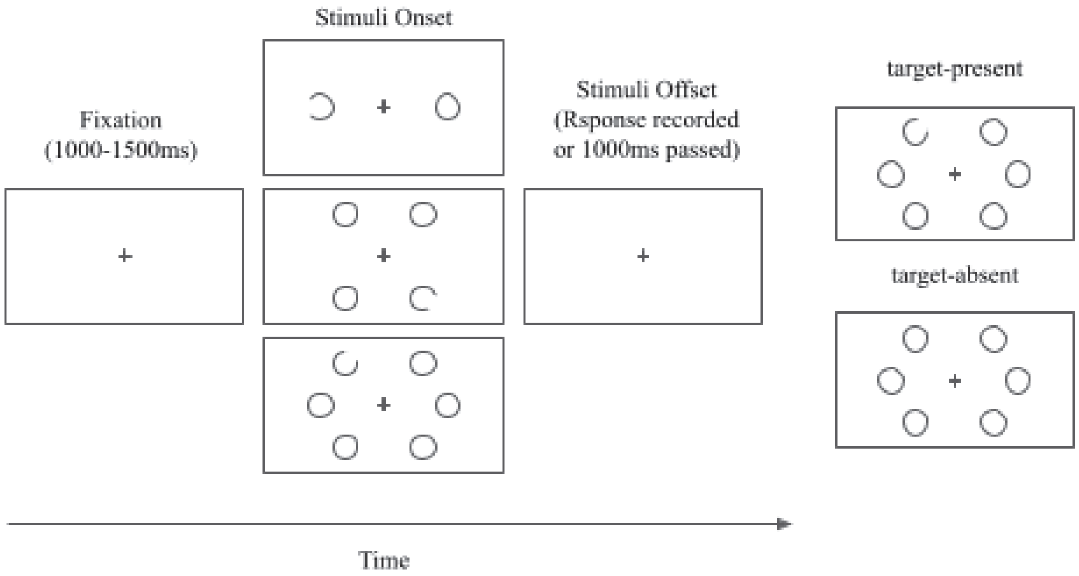


Figure 1. Depicts procedure of stimuli presentation

The experiment was divided into two blocks: one allowed for overt search, while the other required covert search, with no variation in the stimuli presented. Each block consisted of 60 trials for each array size (i.e., 2/4/6), resulting in 360 total trials. Ten percent of the trials were target-absent, while the rest contained one, but no more than one, target. The probability of the target appearing in any given location in the array was equal.

Before the experiment, participants received both oral and written instructions, as well as 20 practice trials. The sequence of the overt and covert search blocks was randomized across participants. A fixation cross was continuously present at the center of the screen during and between trials. Each trial began with a random fixation period between 1000 and 1500 ms, followed by the onset of the search array. Participants were instructed to press button Y on the gaming controller if the target was present and button A if the target was absent. The search array remained on the screen until the response was made or for a maximum of 1000ms. The offset of the search array marked the end of a single trial. The time between the onset of the search array and the button press was recorded as the reaction time (RT). In the covert search block, participants were required to focus their gaze on the fixation cross before and during the trials, while in the overt search block, participants were instructed to focus their gaze on the fixation cross prior to the stimuli onset only.

Electrophysiological Recording

Electrophysiological data were recorded continuously at 2000 samples per second using a DBPA-1 Sensorium bio-amplifier (Sensorium Inc., Charlotte, VT) with an analog high-pass filter of 0.01 Hz and a low-pass filter of 500 Hz (four-pole Bessel). Recordings were made using the 10-10 cap system with 24 Ag-AgCl sintered electrodes (Electrode Arrays, El Paso, TX) while participants were seated in an electrically shielded booth. EEG recordings were made using a forehead ground electrode and a reference at the tip of the nose. All impedances were adjusted to within 0-20 kilohms at the start of the recording session. EEG data were undersampled at 1000Hz and analyzed offline using Brainstorm (Tadel et al., 2011). The data were corrected for ocular artifacts using independent components analysis (ICA).

Eye tracking

Eye movements were recorded using a Tobii pro-Spectrumat a sampling rate of 60hz. The gaze positions recorded on each trial were analyzed using the algorithm developed by (Nyström & Holmqvist, 2010) et al. (2010) to determine the onset and offset times of each saccadic eye movement.

The algorithm developed by Nystrom et al. (2010) functions by detecting not the saccadic movement onset directly, but by finding glissades, a wobbling movement of the eyes that occurs at the end of a saccade (Nyström & Holmqvist, 2010). It also uses an adaptive and algorithmically determined velocity threshold for distinguishing saccadic events, making it less sensitive to variations in noise levels and settings-free for experimenters, therefore eliminating the confounds caused by the subjective selection of thresholds (Nyström & Holmqvist, 2010).

Statistical Analysis

Two of the original 32 participants were excluded from the analysis due to corrupted EEG files, additionally, four participants were excluded due to excessive eye movement during the covert attention condition where eye movements were not allowed. Five more participants were excluded due to insufficient eye movement detected during the overt attention condition where eye movements were allowed. Finally, three participants were excluded due to high error rates, leaving a total of 18 participants in the statistical analysis.

Behavioral Data Analysis

RTs were analyzed using a 2 (Condition: eye movement allowed (E) and eye movement not allowed (NE)) by 3 (Display size: 2 items (Stim2), 4 items (Stim4), or 6 items (Stim6)) repeated measures ANOVA. To enhance clarity, we will utilize abbreviations to denote specific manipulations. For instance, E_Stim2 denotes trials where eye movements are permitted, and the search array consists of two items.

In both NE and E conditions, trials were excluded if an incorrect response was made (2%) or no response was recorded beyond the designated time (0.5%). In the NE condition, trials with a saccade detected before a response was made were excluded (7%). In the E condition, trials with no saccade detected before response (12%) and trials in which the first saccade was toward the hemifield opposite the target were excluded (9%).

Stimulus-locked ERP analysis

All trials, whether covert or overt searches, were segmented from -400ms to 1600ms, time-locked to stimulus onset, and baselined using a 100ms prestimulus period. A band-pass filter of 0.2Hz to 30Hz was subsequently applied, and peak-to-peak bad channel detection was performed with thresholds set at amplitude > 120mV, gradient > 75mV/ms, and std. dev. > 0.001 mV/ms. Any trials with more than 10 (~14%) bad channels were discarded. Each of the channels in those trials with fewer than a total of 10 bad channels was replaced using a spherical spline.

To facilitate ERP calculation and visualization, a montage was applied, subtracting channels ipsilateral to the target hemifield from those contralateral to it. Segments within their respective conditions were then averaged and plotted.

For the identification of the N2pc component, electrode sites PO7 and PO8 were used, with a 20ms measurement window (10ms before and after peak amplitude). Such selection was determined a priori in order to remain consistent with previous research by Dowdall et al. (2012).

Saccade-locked ERP analysis

In the overt search condition, the data were segmented between -600ms and 200ms relative to the onset of the first saccade following target onset, and baselined using a period of -400ms to -300ms. The same band-pass filtering and bad channel rejection as for the stimulus-locked ERP analysis were applied, as well as the same montaging and averaging process.

While the electrode sites of interest remained PO7 and PO8, the measurement window differed. A one-sample t-test was performed for each pre-saccadic negative deflection, with a 20ms time window (peak latency ±10ms). In addition, the post-saccadic negativity reported in Talcot's (2021) research was also investigated.

ERP Image Analysis

The ERP image is a representation of single-trial ERP amplitude (color) over time (X-axis) and trials (Y-axis). When the trials are sorted along the Y-axis with respect to some meaningful behavior, patterns in the ERP image reveal characteristics of the relationship(s) between the ERP amplitude and/or latency of that behavior (Delorme & Makeig, 2004). Rather than averaging over trials, moving-window averaging is used to smooth across time/trials in the ERP image and help to reveal otherwise hidden event-related features in the data (Delorme et al., 2015). Single-trial EEG and theta power were aggregated across Corrected, Correct, and Incorrect trial types. Extreme values in the latency of the kinematic variables were mitigated by trimming trials with values below percentile 0.05 and above percentile 0.95 (i.e., 10% trim) for each ERP image analysis. A two-dimensional Gaussian smoothing filter with a standard deviation of 20 trials (Y-axis) and 1 ms (X-axis) was used to mitigate background noise in the EEG signal (Delorme et al., 2015).

In this study, overt search trials were first segmented into -200ms to 600ms epochs, time-locking to stimuli onset, baselined using a 100ms prestimulus period, and sorted from the fastest first saccadic onset to the slowest from top to bottom for each search array size.

Stepwise time-locking analysis

As described above, the stepwise time-locking analysis is based on the conventional rationale that the timing (i.e., latency) of an ERP is correlated with the timing of a specific cognitive process (Luck, 2014). For a given functional correlate, the latency of the ERP should correspond only with that event's latency and be negligibly correlated with the latency of any flanking cognitive/behavioral events. Likewise, when time-locking the ERP image analysis to those flanking events (i.e., preceding and succeeding the functional correlate) and sorting trials using the functional correlate, strong positive correlations should be observed between the latency of the ERP and the latency of the cognitive/ behavioral event with which the ERP is functionally related.

ERP Image Statistical Analysis

Because widely used techniques for correlation, such as simple regression/Pearson correlation, assume that observations are independent, they are not suitable for determining the strength of the relationships between ERP latencies (or amplitudes) and measures of behavior in ERP images. That is because that data, in the present case, consist of many repeated observations (e.g., trials) from the same participants. Thus, we used the repeated measures correlation (rmcorr) to analyze the common intra-individual association for paired repeated measures (Bakdash and Marusich. 2017). Rmcorr is a variation of ANCOVA. It measures the relationship between two continuous variables while controlling for between-subjects variability in a situation where there are repeated-measures. Like a Pearson correlation coefficient (r), the rmcorr coefficient (r_{rm}) is bounded by −1 to 1 and represents the strength of the linear association between two variables. Notably, determining what constitutes “negligible” and “strong” relationships for the purpose of the stepwise time-locking analysis is complicated in this context by the statistical power imparted by the large number of trials (e.g., >700) that makes most non-zero values of the correlation “statistically significant”. To address this, we considered only “practically” significant results, limiting our interpretations to those correlations (rrm) that were consistent with standard criteria for at least a “large” effect (e.g., rrm20.26) (Cohen, 1988, 1992).

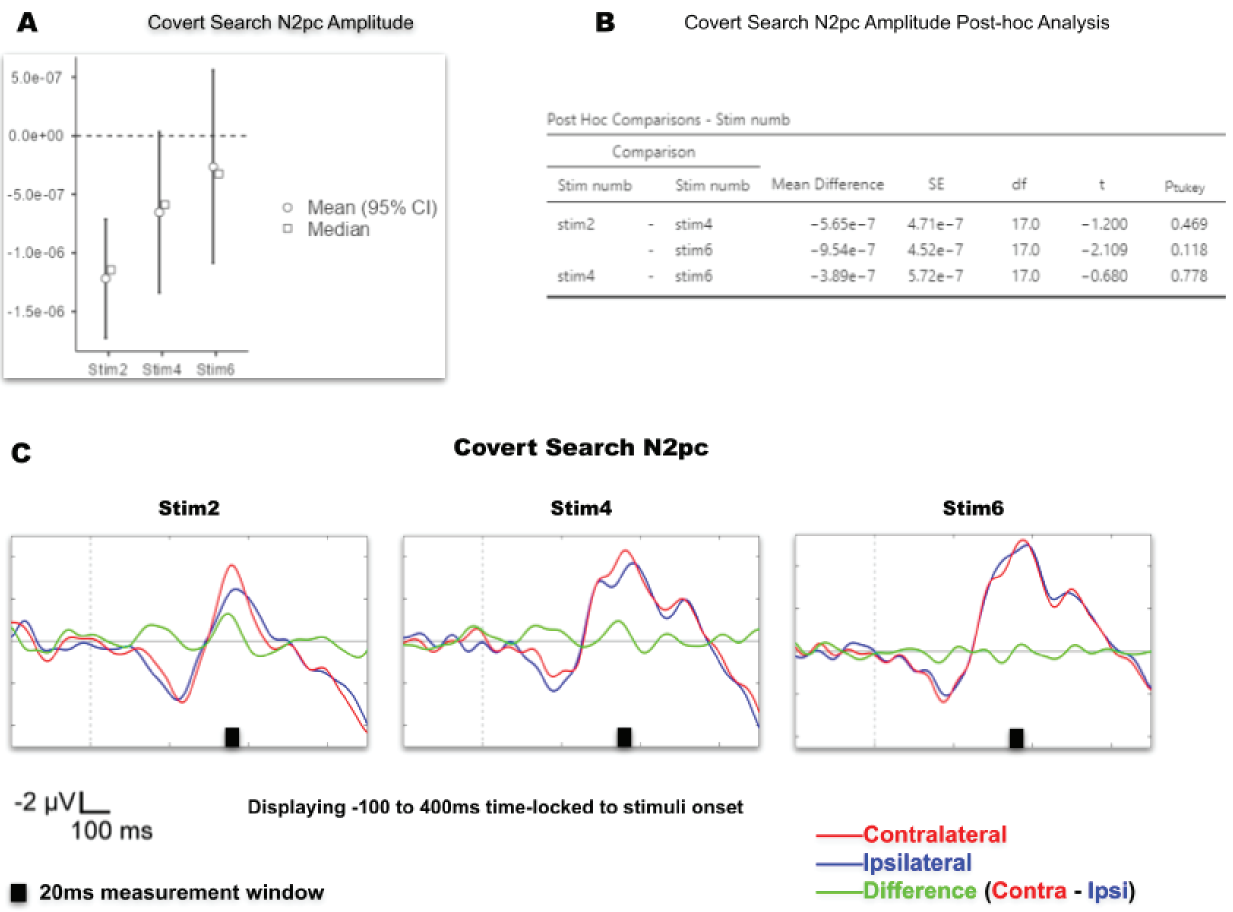
Result

Behavioral **Results:**

The analysis of variance (ANOVA) of RT revealed a significant main effect of attention type, *F*(1, 17) = 14.73, *p* < .001. Post-hoc analyses revealed a difference in mean reaction time between Covert (*M* = 666.9ms) and Overt searches (*M* = 688.5ms) (*p* < .001).

There was also a significant effect of array size, *F*(2, 16) = 32.53, *p* < .001. RT increased monotonically with the size of the stimulus array in both the E and NE conditions. Post-hoc analyses using Tukey's HSD test indicated that the difference between NE_Stim2 (*M* = 645.0ms) and NE_Stim4 (*M* = 658.9ms) was not statistically significant, *p* = 0.799, but that there was a significant difference between NE_Stim4 (*M* = 658.9ms) and NE_Stim6 (*M* = 694.7ms), *p* = .006, as well as between NE_Stim2 (*M* = 645.0ms) and NE_Stim6 (*M* = 694.7ms), *p* < .001. Additionally, the mean RT in the E_Stim2 (*M* = 654.4ms) condition was significantly faster than that in E_Stim4 (*M* = 690.5ms), *p* = .005, and that mean RT in the E_Stim6 (*M* = 720.5ms) condition was significantly longer than that in both the E_Stim4, *p* = .028, and E_Stim2, *p* < .001, conditions.

The interaction between attention type and array size was not statistically significant, *F*(2, 16) = 1.44, *p* = .237.



Post Hoc Comparisons - Stim numb

Comparison							
Stim numb		Stim numb	Mean Difference	SE	df	t	p_{tukey}
stim2	-	stim4	−5.65e−7	4.71e−7	17.0	−1.200	0.469
	-	stim6	−9.54e−7	4.52e−7	17.0	−2.109	0.118
stim4	-	stim6	−3.89e−7	5.72e−7	17.0	−0.680	0.778

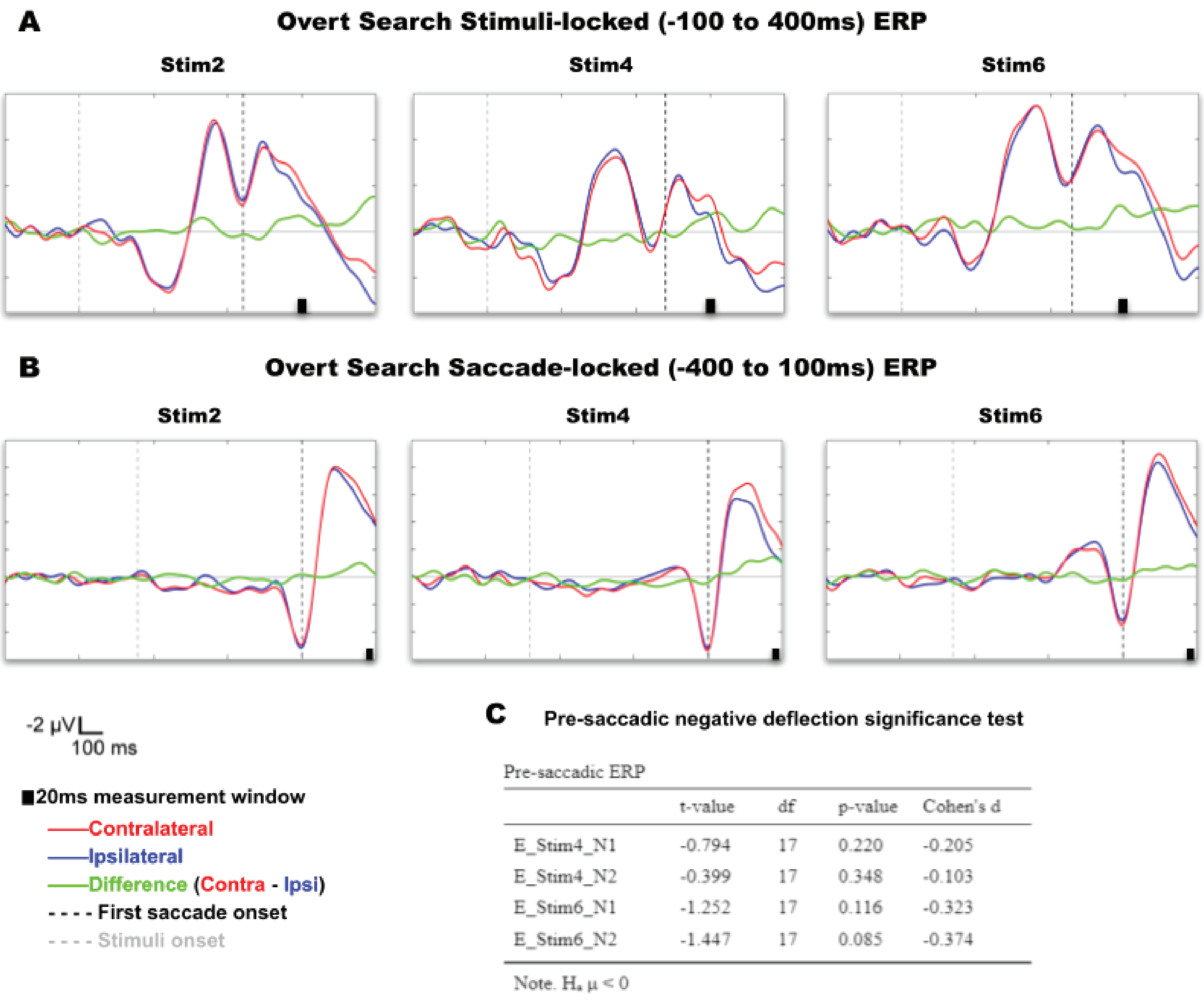
Figure 2: (A) plot of amplitudes of three N2pc components identified in covert searches. (B) table of post-hoc analysis comparing mean differences in amplitudes between covert searches with different search array sizes (C) depicts ERP waveforms of covert searches. The difference in channel contralateral to the target hemifield (red) and ipsilateral one (blue) is depicted in green. A black square is added to indicate the measurement window used.

ERP component analysis

Covert Search Stimulus-locked ERP analysis:

We identified an N2 component approximately 180ms after trial onset (see Figure 2C). Thus, the N2pc was calculated as the mean amplitude between 170ms and 190ms.

A one-sample t-test demonstrated a significant N2pc component in the NE_Stim2 condition, *t*(17) = 4.70, *p* < .001, d = 1.11, and NE_Stim4 condition, *t*(23) = 1.87, *p* = .040, *d* = 0.44. However, we did not observe a significant N2pc component in the NE_Stim6 condition, *t*(23) = 0.63, *p* = .269, *d* = 0.15. Moreover, we found a decreasing amplitude in the N2pc component as the search array grows (see Figure 2A). A repeated measure ANOVA revealed no significant main effect of search array size on N2pc amplitude, *F*(2, 17) = 1.83, *p* = .175. The post-hoc analysis also revealed no significant difference in amplitude between the three search array sizes (see Figure 2B).



C **Pre-saccadic negative deflection significance test**

Pre-saccadic ERP

	t-value	df	p-value	Cohen's d
E_Stim4_N1	-0.794	17	0.220	-0.205
E_Stim4_N2	-0.399	17	0.348	-0.103
E_Stim6_N1	-1.252	17	0.116	-0.323
E_Stim6_N2	-1.447	17	0.085	-0.374

Note. H_a $\mu < 0$

Figure 3. (A) depicts the ERP waveform of overt searches time-locked to stimulus onset (B) depicts the ERP waveform of overt searches time-locked to first saccade onset. (C) table of pre-saccadic negative deflections' one-sampled t-test result.

Overt Search Stimulus-locked ERP analysis:

A much later N2pc-like peak negativity was observed in the E condition at approximately 300ms after trial onset. Thus, the N2pc was calculated as the mean amplitude between 290ms and 310ms.

However, a one-sample t-test revealed that the amplitude of N2pc-like peaks in E_Stim2, $t(17) = 0.16$, $p = 0.437$, $d = 0.04$, E_Stim4, $t(17) = 1.52$, $p = .077$, $d = 0.39$, and E_Stim6, $t(17) = 1.04$, $p = .158$, $d = 0.27$, were not significantly lower than 0.

It is worth noting that, as predicted, no N2pc-like component was detected before the mean saccadic onset in any of the three conditions. Specifically, the mean saccadic onset was 221.2ms, 240.2ms, and 229.4ms for E_Stim2, E_Stim4, and E_Stim6, respectively, with an overall mean saccadic onset of 231.3ms across all conditions.

Overt Search Saccade-locked ERP analysis:

The grand averaged ERP time-locked to the first saccade onset is depicted in Figure 3B. We did not observe any obvious ERP components between mean trial onset and saccadic onset in any of the conditions. To further evaluate this, we conducted a one-sample t-test on two negative-going deflections in the E_Stim4 condition (named E_Stim4_N1 and E_Stim4_N2, identified between -224ms to -219ms and -35ms to -30ms, respectively) and two negative-going deflections in the E_Stim6 condition (named E_Stim6_N1 and E_Stim6_N2, identified between

-176ms to -171ms and -106ms to -101ms, respectively). None of these deflections exhibited an amplitude significantly lower than 0 (see table in Figure 3C). Furthermore, no negative EEG signal was detected between mean trial onset and saccadic onset in the E_Stim2 condition.

Subsequent to the saccadic onset, we identified a negative peak at approximately 85ms in all three conditions. We calculated the mean amplitude between 75ms and 95ms and utilized it as the amplitude for this post-saccadic negativity component. We performed a one-sample t-test to determine if the amplitude was significantly smaller than 0. The post-saccadic negativity component in the E_Stim4 condition yielded a significant result, $t(17) = 2.63$, $p = .010$, $d = 0.68$, while the post-saccadic negativity component in the E_Stim2, $t(17) = 1.18$, $p = .128$, $d = 0.31$, and E_Stim6, $t(17) = 0.87$, $p = .199$, $d = 0.23$, conditions did not exhibit any significant differences from 0.

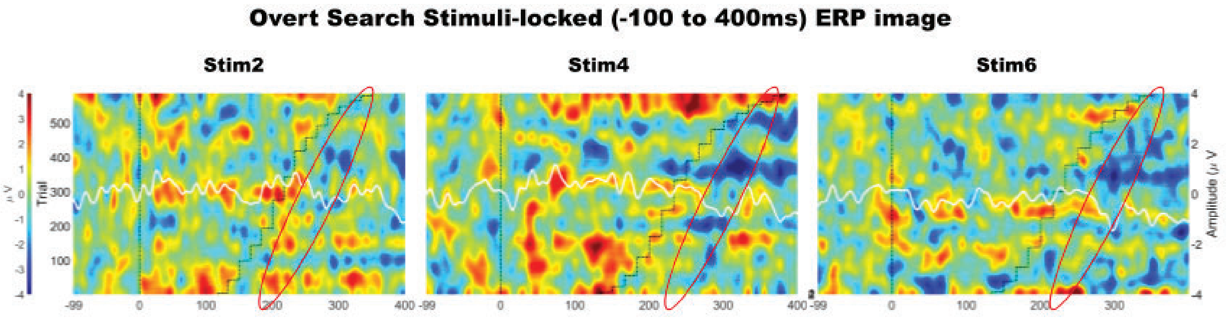


Figure 4. Depicts the ERP image of overt searches time-locked to the stimulus onset. First saccade onset latency is represented by the squiggly line. Circled in red is the negativity belt.

ERP image analysis

Upon analyzing the graphs, we observed the presence of a blue belt following saccadic onset (see Figure 4), which suggests a possible correlation between the latency of the initial saccade and the latency of the post-saccadic negativity. Furthermore, the shades of blue became lighter as the saccadic latency increased, indicating a potential correlation between saccadic latency and post-saccadic negativity amplitude.

To investigate this further, we selected epochs that were time-locked to stimuli onset and sorted them according to the latency of the first saccade. We then identified the most negative point in EEG signal amplitude (calculated using PO7 and PO8, contra-ipsilateral) within each trial, between the time windows of 155ms to 378ms (determined by the earliest and latest first saccadic onset), recorded its latency and amplitude, and conducted a rmcorr analysis to examine the possible correlation between the latency of the first saccade onset with both the latency and the amplitude of the identified negativity.

Using Rmcorr analysis, we found a significant positive correlation between the latency of the first saccade and the post-saccadic negativity latency in the E_Stim2 ($r_{rm}(568) = 0.16$, $p < .001$, 95% CI [0.08, 0.24]) and E_Stim4, $r_{rm}(601) = 0.19$, $p < .001$, 95% CI [0.12, 0.27], conditions, as well as a positive correlation in E_Stim6 that did not reach significance, $r_{rm}(657) = 0.03$, $p = .402$, 95% CI [-0.04, 0.11].

Similarly, we conducted a Rmcorr analysis to explore the possible correlation between the first-saccadic latency and the amplitude of post-saccadic negativity. In the E_Stim4, $r_{rm}(601) = 0.11$, $p = .006$, 95% CI [0.03, 0.19], and E_Stim6, $r_{rm}(657) = 0.14$, $p < .001$, 95% CI [0.07, 0.22], conditions, we found a significant positive correlation. However, in the E_Stim2 condition, we discovered a significant negative correlation, $r_{rm}(568) = -0.27$, $p < .001$, 95% CI [-0.34, -0.19]. It is worth noting that the amplitude of the post-saccadic negativity was smaller than 0, with a positive correlation indicating a smaller amplitude with an earlier saccadic onset and a negative correlation indicating a higher amplitude with an earlier saccadic onset.

Discussion

Behavioral result discussion:

Covert Searches

The first part of hypothesis 1, which suggests that the NE condition should produce efficient searches where no significant increase in reaction time occurs as the number of search items increases, is not entirely accurate. Although we did not observe a significant difference between the mean reaction time in the NE_Stim2 and NE_Stim4 conditions, the mean reaction time for NE_Stim6 was significantly longer than that of NE_Stim4. In contrast, Dowdall et al.'s study reported no significant increase in mean reaction time when the number of search items increased from 2 to 8.

We hypothesize that the significant increase in reaction time from NE_Stim4 to NE_Stim6 may be attributed to hitting the ceiling of our cognitive capacity to simultaneously process the search items. While previous studies did not reveal a similar effect with an even larger number of search items, the difference in participants may have played a role in the present findings.

Overt Searches

The second part of hypothesis 1, which postulates that the E condition should produce inefficient searches where the mean reaction time significantly increases as the number of search items increases, is supported by the data. Our initial hypothesis was that allowing eye movement to assist visual search would lead to participants engaging in inefficient searches, wherein their attention would focus on search items one at a time and would not shift to the next until the previous item had been processed fully. We postulate that this phenomenon could be attributed to the nature of the overt search, which takes advantage of the foveal vision that has high resolution but limited scope.

ERP component result discussion

Covert search

While N2pc components are typically present between 200ms and 400ms after search array onset, it is not uncommon to detect N2pc before 200ms, as several previous studies have reported similar findings (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999).

Of particular interest to us is the decreasing amplitude of N2pc as the number of search items increases, which is an unusual finding. Prior studies have typically reported an opposite finding, where the amplitude of N2pc would either remain constant (Brisson & Jolicoeur, 2007; Woodman & Luck, 2003) or increase as the number of distractors in the search array grows (Eimer, 1996; Hickey et al., 2006; Mazza et al., 2007). The prevailing interpretation of N2pc amplitude is that it reflects the amount of attentional resources deployed in visual search. In feature search tasks, where the target is distinguishable from the distractors with ease, the amount of attentional resources required to detect the target remains largely unchanged with an increase in the search array size, resulting in a constant N2pc amplitude (Brisson & Jolicoeur, 2007; Woodman & Luck, 2003). In contrast, in conjunction search tasks, where the target cannot be easily distinguished from the distractors, the difficulty of the search task tends to increase with an increase in the search array size, requiring more attentional resources and resulting in an increasing N2pc amplitude (Eimer, 1996; Hickey et al., 2006; Mazza et al., 2007).

However, the design of the studies cited above is considerably different from ours. The prior studies involved targets and distractors that differed in more than one aspect (such as shape, color, or orientation) or included general noise distractors, such as a search array consisting of white L's in the background with a green T and a red T as the distractor and target, respectively (Talcott & Gaspelin, 2021). While only a few studies report a decrease in N2pc amplitude with larger search arrays, other related studies may provide valuable insights into why this phenomenon occurs.

One explanation proposed by Lavie et al. is that attentional resources may become spread more thinly across items as the search array size increases, resulting in a decrease in N2pc amplitude (Lavie, 2005). This interpretation suggests that the N2pc amplitude reflects the amount of attentional resources allocated to target processing, rather than the total amount of attentional resources deployed, as the N2pc is measured at the contralateral side of the target hemifield.

Another possible explanation for this phenomenon is temporal variability. Our analysis of reaction times indicated that visual search in the NE condition lacked a strong pop-out effect. This suggests that with larger search arrays, the time required for the visual system to process all items and locate the target may increase, resulting in a delayed or attenuated N2pc component.

Overt search

The examination of ERP components during visual search aided by eye movements revealed results similar to Talcot's study, where no N2pc-like component was identified prior to saccadic onset. Our hypothesis 3 was corroborated. However, unlike Talcot's findings, none of the N2pc-like components identified after saccadic onset were significant.

Several factors may explain the absence of significant ERP components. Specifically, we observed great temporal variability in the first saccadic onset latency in all three conditions, ranging over 200ms from the earliest to the latest. If the N2pc-like component is time-locked to saccades, such temporal variability might render it invisible after grand averaging.

Our findings of a significant post-saccadic negativity component in the E_Stim4 condition partially supported the temporal variability in saccade onset theory. While the post-saccadic negativity component in E_Stim2 and E_Stim6 was not significant, their amplitudes were larger than that of the N2pc-like component counterpart.

Furthermore, our RT analysis revealed that overt searches are serial, suggesting that despite our effort in excluding trials where the first saccade was directed towards the wrong hemifield, there was still temporal variability in overt attention landing on the target after the first saccade was launched. This variability be exacerbated when multiple search items are present in a single hemifield. Such layered temporal variability renders grand averaging unsuitable for our purpose, which is to examine the possible time-lockedness between the post-saccadic negativity and saccadic onset.

ERP image result discussion

The positive correlation identified between first saccade latency and the latency of the largest negativity, though not significant in the E_Stim6 condition, shows support for our hypothesis of possible time-lockedness between post-saccadic negativity and first saccade onset.

The lack of significance in the positive correlation between first saccade latency and the latency of the largest negativity in E_Stim6 might be a result of the rmcorr method. Upon inspecting the plot depicting the correlation, we found that in a considerable amount of trials, the largest negativity is identified prior to the saccade onset, early into the trials, which fails to capture our interest, the post-saccadic negativity, thus undermining the correlation. The analysis performed in E_Stim2 and E_Stim4 conditions also suffers from a similar drawback, resulting in an attenuated rrn.

The correlation between first saccade latency and the largest negativity amplitude return a mixed result with two conditions being positively correlated and one condition being negatively correlated. We cannot establish a relationship between the amplitude of the N2pc-like negativity and the latency saccadic onset based on the statistical result.

Compromises

Inevitably, the current study possesses certain limitations and entails concessions throughout its implementation.

Eye tracking recoding

In the original investigation conducted by Talcott et al. (2021), an SR Research EyeLink 1,000+ eye tracker with a 500 Hz sampling rate was utilized, and the resultant data were processed using the EyeLink Toolbox, a MATLAB add-on, with manually determined velocity and acceleration thresholds. Our laboratory is equipped with a Tobii Pro-Spectrum eye tracker, which operates at a 60 Hz sampling rate and lacks the capability for automatic recalibration during the procedure once initially set. The discrepancy in eye tracker performance could potentially introduce undesired distortions in the data if Talcott's EyeLink Toolbox settings are implemented without modification. Consequently, we have opted to employ the algorithm developed by Nyström et al. (2010) to ascertain the onset of the first saccadic movement.

Traditional algorithms for saccade detection, such as the one employed by the EyeLink Toolbox and adopted by Talcott et al. (2021), typically necessitate manual input of velocity and acceleration thresholds for detection (Brainard, 1997; Kleiner et al., 2007; Nyström & Holmqvist, 2010; Pelli, 1997). However, these manually selected thresholds are frequently chosen based on heuristics or by merely conforming to existing paradigms or settings from prior studies (Nyström & Holmqvist, 2010). Nyström et al. (2010) contend that employing such practices with different eye tracker models can introduce distortions, thus motivating the adoption of their algorithm in the current study.

Notwithstanding, while our first saccade latency (231.3 ms) is comparable to Talcott's (2010) findings (221 ms), it remains uncertain how the divergence in algorithms may influence the determination of the first saccade latency.

Ocular Artifact Removal

Talcott et al. (2021) and Dowdall et al. (2012) adopted a more conservative approach to ocular artifact removal in their investigations compared to the present study. Rather than subjecting the entire electroencephalogram (EEG) file to independent component analysis (ICA) cleaning, they eliminated blink artifacts on a trial-by-trial basis. Furthermore, Talcott et al. only removed horizontal eye movement artifacts in the covert search condition, retaining them in overt search trials.

This discrepancy in data cleaning methods could potentially result in differences in event-related potential (ERP) amplitudes. As such, we advise exercising caution when analyzing and comparing ERP components between the current study and previous investigations.

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