Eye Movements Are Not Mandatorily Preceded by the N2pc Component

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Travis N. Talcott* and Nicholas Gaspelin

Binghamton University, State University of New York

Abstract

Researchers typically distinguish between two mechanisms of attentional selection in vision: overt and covert attention. А commonplace assumption is that overt eye movements are automatically preceded by shifts of covert attention during visual search. Although the N2pc component is a putative index of covert attentional orienting, little is currently known about its relationship with overt eye movements. This is because most previous studies of the N2pc component prohibit overt eye movements. The current study assessed this relationship by concurrently measuring covert attention (via the N2pc) and overt eye movements (via eye tracking). Participants searched displays for a lateralized target stimulus and were allowed to generate overt eye movements during search. We then assessed whether overt eye movements were preceded by the N2pc component. The results indicated that saccades were preceded by an N2pc component, but only when participants were required to carefully inspect the target stimulus before initiating the eve movement. When participants were allowed to make naturalistic eye movements in service of visual search, there was no evidence of an N2pc component before eve movements. These findings suggest that the N2pc component does not always precede overt eye movements during visual search. Implications for understanding the relationship between covert and overt attention are discussed.

Keywords

Selective Attention Eye Movements Visual Search Eye Tracking N2pc

1. Introduction

In everyday life, we frequently search complex visual scenes for objects that are relevant to our immediate goals. For example, we may search our apartment for a lost set of keys or search the kitchen counter for an ingredient while preparing a meal. To accomplish this, we can overtly direct our eyes to objects of interest to allow them to benefit from the high-resolution information provided by the fovea (Henderson, 2003). In addition, we can covertly shift attention to objects of

interest to allow them to benefit from enhanced cortical processing (Kastner & Ungerleider, 2000). Importantly, shifts of covert attention can occur in the absence of eye movements (Posner, 1980; Woodman & Luck, 1999) and are initiated rapidly in comparison to eye movements (e.g., 50–150 ms after stimulus onset; Chelazzi et al., 1998; Horowitz et al., 2009). Therefore, it is frequently assumed that shifts of covert attention are used to guide subsequent eye movements.

One technique to study covert attentional allocation has come from event-related potential (ERP) studies of the N2-posterior-contralateral (N2pc) component (Eimer, 1996; Foster et al., 2020; Gaspelin & Luck,

2018a: Hickey et al., 2009: Luck & Hillvard, 1994b: Tan & Wyble, 2015; Woodman & Luck, 1999). The N2pc component is a negative-going deflection that occurs over contralateral visual cortex approximately 200-300 ms after stimulus onset, and it is widely assumed to index some aspect of covert attentional selection. For example, Luck and Hillyard (1994) demonstrated that search targets typically elicit an N2pc component and proposed that the N2pc component measures the filtering of distractors around a covertly attended location (but see Hickey et al., 2009; Mazza et al., 2009a, 2009b). Others have suggested that the N2pc component may measure shifting of covert attention (Tan & Wyble, 2015), individuation of the attended object (Foster et al., 2020), or attentional engagement on a search item (Zivony et al., 2018). In any case, the N2pc component is commonly used to infer whether a given search item was covertly attended during visual search.

The relationship between the N2pc component and eve movements, however, is not well understood. This is because most previous studies of the N2pc component have explicitly prohibited eve movements. Eye movements generate large artifactual voltagessuch as corneoretinal potentials (Lins et al., 1993) and oculomuscular spike potentials (Thickbroom & 1986)—which can make the N2pc Mastaglia. component difficult to interpret. As a result, most studies of the N2pc component prohibit eye movements and use techniques at analysis to either eliminate trials with eye movements (e.g., Luck et al., 1997; Woodman & Luck, 2003) or use independent component analysis (ICA) to correct the EEG waveforms for eye movement artifacts (Drisdelle et al., 2017). Although these approaches are useful for ensuring that an observed N2pc component is truly due to a shift of covert attention and not merely eye movement related artifacts, it is also extremely artificial. As a result, little is known about how the N2pc component is coordinated with overt eye movements during visual search.

A common assumption is that covert attention is used to guide overt eye movements during visual search. Indeed, an abundance of psychophysical studies indicate that covert attention is automatically deployed to the destination of an upcoming eye movement before it is generated (Beauchamp et al., 2001; Deubel & Schneider, 1996; Gaspelin et al., 2017; Irwin & Gordon, 1998; Khan et al., 2011; Kowler et al., 1995; Moore & Fallah, 2001, 2004; Rayner, 2009; Rolfs et al., 2011; Schall & Thompson, 1999; Smith & Henderson, 2011: Theeuwes et al., 1998: Wolfe, 2020; Wu & Remington, 2003). For example, in a now seminal study, Hoffman and Subramaniam (1995) used a central arrow cue to indicate an upcoming saccade target destination from four possible locations. After a delay (1500-300 ms), a tone was played to signal the participant to execute the saccade. Just before the saccade was initiated, three distractor probe letters (E or F) and one target probe letter (T or L) briefly appeared on each of the potential saccade destinations (e.g., for 11 ms). Participants were asked to report whether a T or L letter probe had been presented. Critically, probe report accuracy was improved for probes that appeared at the location of the upcoming saccade compared to other locations. This pattern of results seems to indicate that a shift of covert attention typically precedes eye movements.

Despite the commonplace assumption that covert attention typically precedes overt eye movements, little is known as to whether the N2pc component-a putative index of covert attentional allocationprecedes eye movements generated during visual search. Only a handful of studies have assessed N2pc components that occur before eye movements (Huber-Huber et al., 2016; Luck et al., 1997, Experiment 3; Weaver et al., 2017). For example, Weaver and colleagues (2017) had participants covertly search displays of vertical lines and generate eye movements to a uniquely oriented line. At analysis, ERPs were timelocked to the onset of the saccade, and neural activity before the saccade was examined for an N2pc-like contralateral negativity. This clever technique avoids eye movement artifacts, which should not occur before the first saccade is generated. Interestingly, this study found that, when the eyes were successfully directed to the target stimulus, there was a contralateral negativity beginning about 50 ms before the first eye movement. This presaccadic N2pc component was taken to indicate that the target stimulus was covertly attended before an eve movement was generated.

Although Weaver and colleagues (2017) provided clear evidence that eye movements can be preceded by an N2pc component (see also Huber-Huber et al., 2016; Krebs et al., 2012; Luck et al., 1997), this study does not definitively answer whether the N2pc component will always precede eye movements. There are two reasons to suspect that eye movements are not always preceded by an N2pc component. First, eye movements are often generated too quickly to be preceded by an N2pc component. Many previous studies have found that eye movements can be

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generated rapidly (ca. 175-225 ms) during visual search (Beck & Hollingworth, 2017; Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018b; Henderson, 2003; Kruijne & Meeter, 2016; Mulckhuyse et al., 2008: Shurygina et al., 2019; Talcott & Gaspelin, 2020), whereas the N2pc component typically occurs during a later time period (ca. 200-300 ms; Hickey et al., 2009; Kiss et al., 2008; Luck & Hillyard, 1994; Woodman & Luck, 1999, 2003). In previous studies of the presaccadic N2pc component, the latency of first eye movements to the target were relatively slow (ca. 275-325 ms) which is likely because participants were required to direct gaze to the target stimulus as a response as opposed to naturally generating eye movements in service of search (Huber-Huber et al., 2016; Weaver et al., 2017). A second reason to suspect that the N2pc does not always precede eye movements is theoretical in nature. If the N2pc reflects the focusing of covert attention on a search item, it is unclear why this cognitive process would always need to occur before an eye movement is generated (see Luck, 2009). Many features (e.g., color) can be detected preattentively and would not require a shift of covert attention to be known (Treisman & Gelade, 1980; Wolfe & Horowitz, 2017). In such cases, it seems suboptimal for the oculomotor system to mandatorily wait for covert attention before generating an eye movement.

To summarize, it is currently unclear whether the N2pc component automatically precedes every eye movement generated during visual search. Although some previous studies have shown that N2pc components can occur before eye movements, most of these studies employed experimental approaches (e.g., saccade-to-target paradigms) that slowed saccadic latencies (ca. 275-325 ms). The current study will assess N2pc components that occur before naturalistic eye movements during visual search (ca. 175-225 ms). To preview the results, we observe robust N2pc components before eve movements, but only under experimental conditions that force covert attention to be deployed before an eye movement is generated. We find no evidence of a presaccadic N2pc component when naturalistic eye movements are freely generated in service of visual search.

2. Experiment 1

Experiment 1 assessed whether the N2pc component mandatorily precedes naturalistic eye



Figure 1. Stimuli and procedure for Experiment 1. Participants were required to maintain central fixation to initiate the trial. Next, a search array appeared in which participants searched for a target square of a specific color (e.g., green) and reported whether the location of the gap (top or bottom). In the covert search condition, participants searched for the target-colored square without making eye movements. In the overt search condition, participants performed the same basic search task, but were allowed to make overt eye movements to find the target-colored square. The gaps were slightly smaller in this condition to encourage overt eye movements.

movements generated during visual search. As shown in Figure 1, participants searched for a target square of a specific color (e.g., green) amongst gray squares and reported the location of a gap (top or bottom) via manual buttonpress. The experiment was divided into two conditions. In the covert search condition, eye movements were prohibited, as in most previous studies of the N2pc component (Woodman & Luck, 1999). In the overt search condition, participants were allowed to freely generate eye movements. Importantly, eye movements were not required as a response to the target (as in Huber-Huber et al., 2016; Weaver et al., 2017) and participants responded via manual buttonpress.

In the covert search condition, we expect to observe an N2pc component to the target, replicating previous studies (Woodman & Luck, 1999, 2003). The critical question is whether an N2pc component to the target will occur before the first eye movement in the overt search condition. If initiating eye movements to a target requires a preceding shift of covert attention, we should observe a presaccadic N2pc component (i.e., a negative-going deflection contralateral to the target before eye movements were directed to the target). However, if initiating an eye movement to a target does not require an initial shift of covert attention, there should be no N2pc component before eye movements directed to the target.

2.1 Method

2.1.1 Participants

Twenty-four undergraduate students from the State University of New York at Binghamton participated for monetary compensation (14 women, 10 men). All participants were between the ages of 18 and 30 (M_{age} = 20.0 years). The sample size was determined a priori based upon previous studies of the presaccadic N2pc component. Based upon the effect size of the presaccadic N2pc (η^{2}_{p} = 0.70) in Weaver et al. (2017), this sample size should yield .99 power to detect a presaccadic N2pc. All participants had normal or corrected-to-normal visual acuity and normal color vision as assessed by an Ishihara test.

2.1.2 Apparatus

Stimuli were presented using PsychToolbox (Brainard, 1997) for Matlab on an Asus VG245H LCD monitor at a viewing distance of 100 cm in a dimly lit room. A photosensor was used to measure the timing delay of the monitor (12 ms) and all data were adjusted offline to compensate for this delay.

2.1.3 Stimuli and Procedure

The search task was based upon prior studies of the N2pc component (Figure 1; Woodman & Luck, 1999, 2003). Each stimulus array was presented within a 10° by 6° region and consisted of 16 squares arranged in a grid-like pattern. The outline of each square was 0.1° thick and subtended 1° in width and height. Each square had a small gap (overt search: 0.02°, covert search: 0.3°) on the top or bottom. Each search array contained one green square (38.5 cd/m², x = .287, y = .414) and one red square (38.5 cd/m², x = .364, y = .294). These colored squares appeared directly to the left and right of the fixation cross (3°) . Participants searched for a target square of a specific color (e.g., green), which was counterbalanced across participants. The location of the target-colored square was selected at random, and the distractor-colored square always appeared in the opposite hemifield. The remaining fourteen squares were gray (38.5 cd/m², x = .298, y = .313) and were distributed throughout the 10° by 6° stimulus array. The precise locations of both colored squares were fixed, but the location of each gray square was randomly jittered by up to 0.4° on each trial. A gray fixation dot (0.3° radius) with a black crosshair (0.06° thickness) was continually present. All

stimuli appeared on a black background. Each trial began with a fixation cross, and participants were required to maintain gaze position within 1.5° of the screen center for 500 ms. Once participants met this requirement, the search array appeared. Participants searched for the target square and reported the location of its gap (top vs. bottom) using the right shoulder-buttons on a gamepad (bumper vs. trigger buttons, respectively). If the participants made an incorrect response, a 200-Hz tone sounded for 300 ms. If participants were too slow to respond (greater than 2000 ms), a timeout display with the text "Too Slow!" appeared. A random jitter delay between 0 and 500 ms occurred at the end of each trial to prevent entrainment of the EEG to the stimulus stream.

There were two experimental conditions (Figure 1). In both conditions, participants searched for the targetcolored square and reported the location of the gap in the square (top vs. bottom) via manual buttonpress. In covert search blocks, eye movements were prohibited, as in most prior N2pc experiments (Eimer, 1996; Gaspelin & Luck, 2018a; Hickey et al., 2009; Tan & Wyble, 2015; Woodman & Luck, 1999, 2003). The gaps in each square were large enough (0.3°) to be discriminated from central fixation. If gaze position exceeded 1.5° from central fixation, a 200-Hz tone sounded for 300 ms and a message appeared reminding the participants to refrain from moving their eyes ("No Eye Movements!"). In overt search blocks, participants performed the same search task but were allowed to make eye movements. To encourage eye movements, the gaps in the squares were too small (0.02°) to be discriminated from central fixation (see Gaspelin et al., 2017, 2019; Talcott & Gaspelin, 2020).

The experiment was divided into two halves (overt and covert search) and the order of conditions was counterbalanced across participants. After receiving instructions for a given condition, participants first completed one practice block of 96 trials followed by four blocks of 192 trials for that condition. This yielded 768 trials per condition in the final data analysis. Participants received feedback on their performance after each block via a screen that displayed the mean response time and accuracy.

2.1.4 Eye tracker recordings

An SR Research Evelink 1000+ desk-mounted system recorded eye position monocularly from the right eye at 500 Hz. A remote-mode configuration was used to allow eye tracking without a chinrest that would cause muscular EEG artifacts. The Eyelink Toolbox was used to interface the eyetracking and stimulus presentation systems (Cornelissen et al., 2002). The onset of a saccade was defined using minimum velocity (30°/s) and acceleration $(9500^{\circ}/s^{2})$ thresholds. Before each block began, participants completed a five-point calibration procedure to calibrate the eye-tracker system. If participants failed to maintain central fixation for more than 8 seconds during the fixation period of a trial, the eye-tracker system was recalibrated. Our eye-tracking analyses focused on the destination of the first saccade on each trial. The first saccade on each trial was classified as the first eye movement to leave central fixation and land within 3° from the center of either colored square.

2.1.5 Electrophysiological recordings

EEG was recorded using active Ag/AgCl electrodes (Brain Products actiCHamp) from a set of standard scalp sites (FP1, FP2, F3, F4, F7, F8, C3, C4, P3, P4, P5, P6, P7, P8, P9, P10, P03, P04, P07, P08, 01, 02, Fz, Cz, Pz, POz, Oz). Additionally, recordings were obtained from the left and right mastoids as a reference. Horizontal eye movements were measured with the horizontal electrooculogram (HEOG), and vertical eye movements and blinks were measured with the vertical EOG. The data were analyzed using EEGLAB Toolbox (Delorme & Makeig, 2004) and ERPLAB Toolbox (Lopez-Calderon & Luck, 2014). The data were referenced offline to the average of both mastoid electrodes. Impedances were kept at or below 10 K Ω for all electrodes. A customized version of the PyCorder recording software filtered the EEG data online with a cascaded integrator-comb antialiasing filter with a half-power cutoff at 130 Hz and then digitized with a 500-Hz sampling rate. These signals were then filtered offline using a noncausal Butterworth high-pass filter (half-amplitude cutoff: 0.1 Hz, slope: 12 dB/octave).

2.1.6 EEG and Eye Tracking Synchronization

Eve movements and EEG data were measured concurrently, and event codes were simultaneously sent to the eye tracking system and EEG system via a parallel port splitter. The eye tracking and EEG data were then combined after the experimental session using the EYE-EEG Toolbox (Dimigen et al., 2011). During analysis, a regression-based approach was employed to ensure that the time points of the event codes in the EEG waveforms and eye-tracking data were synchronized. The times of the event codes in the EEG and eye-tracking files were perfectly correlated (R² = 1.00 for all participants) and the average latency difference between EEG and eye tracking files was 0 ms (± 2 ms). As an additional confirmation of the quality of synchronization, bipolar HEOG and gaze position data were time-locked to the onset of the first saccade detected by the eye tracker. We then generated plots of bipolar HEOG and gaze position for left- vs. right-hemifield targets that were time-locked to the first saccade. These plots showed no evidence of a lateralized divergence in bipolar HEOG before the first eve movement (for details, see the Supplemental Material).

2.1.7 Behavioral data analysis

Trials were excluded from analysis if they contained an incorrect response (2%) or an abnormal manual RT (less than 200 ms or greater than 1500 ms, 0.2%). In the overt search condition, trials with an abnormal saccadic latency were also excluded (less than 50 ms or greater than 1000 ms; 0.6%). Additionally, trials were excluded if they did not contain a saccade that left central fixation and landed within 3° of the center of a colored square (6% of all overt search trials with a saccade). Trials containing inaccurate manual responses were excluded from all analyses except for analyses of error rates. Analyses of manual RT, error rates, and saccadic latency were computed using paired-sample t tests.

2.1.8 Stimulus-locked ERP analysis

Stimulus-locked ERP waveforms were computed similar to previous studies of the N2pc component in both the covert and overt search conditions (Gaspelin & Luck, 2018a; Woodman & Luck, 1999, 2003). We first established a 600-ms epoch, beginning 200 ms before the onset of the search array. The EEG signal was baselined using the 200-ms prestimulus period. The epoched EEG data was then screened for common artifacts and these trials were removed from further analysis. Eyeblinks were identified as step-like voltage changes exceeding 80 μ V in the epoch window. We also excluded trials with unusually large voltage deflections (greater than 100 μ V) in any channel.

In the overt search condition, trials were not excluded for eve movement artifacts. In the covert search condition, eve movement artifacts were identified via step-like changes exceeding 16 µV over a 100 ms window in the HEOG signal between 100 and To assess whether the 400 ms poststimulus. remaining data were contaminated by small eve movements, we first computed averaged HEOG waveforms for the left- and right- target trials and participants were then replaced if the waveforms for left-versus right-target trials deviated by more than 3.2 µV (see Woodman & Luck, 2003). This ensures that the remaining participants had an average eve rotation of less than ± 0.1° (Lins et al., 1993). Four participants were replaced for this reason. We always replaced the data from both conditions for a participant if the number of trials rejected for artifacts in the EEG or EOG signal exceeds 25% of trials in either condition (see also Gaspelin & Luck, 2018a). In the final sample, an average of 13.9% of trials were excluded for EEG and EOG artifacts in the covert search condition.

To avoid Type I errors (Luck & Gaspelin, 2017), the measurement window and electrode sites for the N2pc component were determined a priori on the basis of prior studies (Eimer, 1996; Gaspar & McDonald, 2014; Hickey et al., 2009; Luck & Hillyard, 1994b; Woodman & Luck, 1999, 2003). The N2pc was measured as the difference in mean amplitude between contralateral and ipsilateral waves relative to the location of the target at the P07 and P08 electrode sites, with a measurement window of 200–300 ms.

2.1.9 Saccade-locked ERP analysis

In the overt search condition, saccade-locked ERPs were calculated by time-locking to the first saccade rather than to the stimulus onset (Weaver et al., 2017). We established a 700-ms epoch window that began 500 ms before the first saccade. The EEG signal was baselined on each trial using the 200-ms prestimulus period (Huber-Huber et al., 2016). Trials were excluded from analyses if they did not contain an eye movement (<0.1%). Additionally, we excluded EEG artifacts using the same procedures for the stimulus-locked ERPs (eyeblinks, unusually large voltages), except that trials were not removed for eye movement

artifacts in the EOG. We also replaced the data in both conditions for a participant if the number of trials rejected for artifacts in the EEG signal exceeded 25% of trials in either condition. One participant was replaced for this reason. In the final sample, 3.2% of trials were excluded for EEG artifacts.

To analyze the presaccadic N2pc, we used the same electrode sites (PO7/PO8) as the stimulus-locked ERPs. Few studies have investigated the presaccadic N2pc, which made it challenging to determine an appropriate time window. We therefore used two time windows: (1) an a priori time window that began 50 ms before the first saccade (based upon Weaver et al., 2017), and (2) an a priori time window that began 100 ms before the first saccade (based upon Huber-Huber et al., 2016). With both strategies, one-sample t tests were used when the N2pc amplitude was compared to zero using an a priori time window.

2.1.10 Code and Data Availability

All stimulus scripts, data, and analysis scripts are available online on the Open Science Framework at <u>https://osf.io/8wkas/?view_only=fb9ab2daebe6490</u> <u>9b30c3437d77430e6</u>.

2.2 Results

2.2.1 Manual RT and Error Rates

Manual RT was faster on covert search blocks (628 ms) than overt search blocks (804 ms), t(23) = 15.24, p < .001, $d_z = 3.11$. This is likely due to the larger gap size in the covert search condition than overt search condition. Error rates were slightly higher on covert search blocks (2.5%) than on overt search blocks (1.8%), t(23) = 3.01, p = .006, $d_z = 0.62$. This suggests that manual response errors were more likely when participants classified the location of the gap using parafoveal vision (covert condition) than using foveal vision (overt condition).

2.2.2 Saccade Destination and Latency

Figure 2A depicts heat maps of first saccade landing position for left- and right-target trials, aggregated across trials and participants in the overt search condition. As can be seen, first saccades were much more likely to be directed to the target-colored square than to the distractor-colored square.

As a more formal analysis, the saccade data were



Figure 2. Eye movement results from the overt search condition of Experiment 1. As can be seen, eye movements were strongly guided to the target-colored square. (A) Heat maps of first saccade landing positions for both potential target locations (left vs. right). (B) Percentage of first saccades to the target and distractor item collapsed across both target locations.

pooled across left-target and right-target trials. We then assessed whether the first eye movement landed on the target-colored square or on the distractor-colored square. Figure 2B depicts the percentage of first saccades directed to each item type. As can be seen, first saccades were much more likely to be directed to the target-colored square (75.4%) than to the distractor-colored square (24.6%), t(23) = 9.148, p < .001, $d_z = 1.87$. This pattern of results clearly

indicates that first saccades were guided toward the object with the target color.

We also analyzed the latency of the first eye movement for each trial as a function of which item was first fixated (target-colored square or distractor-colored square). First saccades directed to the target-colored square (206 ms) were slower than first saccades directed to distractor-colored square (182 ms), t(23) = 10.50, p < .001, $d_z = 2.14$. This is



Figure 3. Stimulus-locked ERPs from Experiment 1, which were time-locked to the onset of the search array, just as in traditional ERP studies. (A) and (B) depict ERP waveforms for electrode sites ipsilateral and contralateral to the target in the covert search and overt search conditions. In the overt search condition (B), mean first saccade latency is depicted as a blue vertical line. A histogram of first saccade latencies is shown below the ERP waveform. (C) Difference waveforms created by subtracting ipsilateral waveforms from contralateral waveforms. All figures of ERP waveforms in this study were low-pass filtered to improve visibility (Butterworth noncausal filter, half-amplitude cutoff = 20 Hz, slope = 12 dB/octave).

consistent with previous studies suggesting that topdown mechanisms involved in guiding eye movements may take additional time to initiate (Gaspelin et al., 2017; van Zoest et al., 2004).

2.2.3 Stimulus-Locked ERPs

Figure 3A and 3B depict stimulus-locked ERP waveforms for covert and overt search conditions, respectively. These waveforms for lateral occipital scalp sites (PO7 and PO8) were time-locked to the onset of the stimulus array, just as in traditional studies of the N2pc (Luck & Hillyard, 1994b; Woodman & Luck, 1999, 2003). Separate waveforms are shown for ipsilateral and contralateral sites relative to the target location. For example, the contralateral waveform depicts the average of the left-hemisphere electrode (PO7) on trials where the target appeared on the right and right-hemisphere electrode (PO8) on trials where the target appeared on the left. In overt search blocks, grand-averaged waveforms depict only trials where the first saccade was directed to the target. The histogram below the ERP waveform depicts the distribution of Figure 3C depicts difference saccadic latencies. waveforms that were computed by subtracting the ipsilateral waveform from the contralateral waveform.

In covert search blocks (Figure 3A), the N2pc component appears as a negative-going deflection beginning approximately 180 ms poststimulus and peaking approximately 250 ms poststimulus. To formally analyze this, the mean amplitude of the difference waveform was measured from 200 to 300 ms and a preplanned one-sample t test confirmed that the mean amplitude (-0.6 μ V) was significantly less than zero, t(23) = 4.89, p < .001, d = 1.00.

In overt search blocks (Figure 3B), there was also an N2pc-like component in approximately the same time range and this difference waveform (-1.1 μ V) was also significantly less than zero, t(23) = 6.37, p < .001, d = 1.30. Importantly, this N2pc-like component occurred after the mean first saccade onset time (206 ms). Thus, this contralateral negativity could be due to extraocular artifacts generated by the eye movement, instead of a true N2pc component (Lins et al., 1993; Woodman & Luck, 1999). This issue is directly resolved in the next section by time-locking to the first saccade, effectively eliminating any extraocular artifacts in ERP waveform before timepoint zero.

2.2.4 Saccade-Locked ERPs

In overt search blocks, the key question is whether first saccades that were guided to the target were preceded by an N2pc component, indicating covert attentional selection before the eye movement. To assess this, Figure 4A depicts grand-averaged ERP waveforms time-locked to the onset of the first saccade. Thus, voltages leftward of timepoint zero reflect neural activity before the first saccade, whereas voltages rightward of timepoint zero reflect neural activity after the saccade. The ERP waveforms depict occipital scalp sites (PO7 and PO8) with separate waveforms for contralateral and ipsilateral sites relative to the target location. Analyses were constrained to trials where the first saccade was directed to the target. The average onset of the search array is depicted as the vertical line 206 ms before the first saccade. Figure 4B depicts difference waveforms calculated by subtracting ipsilateral waveforms from the contralateral waveforms. Figure 4C depicts scalp topography maps averaged in 100 ms intervals (see Sawaki et al., 2012).

As can be seen, there is no evidence of a negativegoing contralateral voltage (a presaccadic N2pc) before the first saccade. To formally assess this, we calculated mean amplitude of the contra-minus-ipsi difference waveform (Figure 4B) from -50 to 0 ms (as in Weaver et al., 2017). A one-sample t test confirmed that there was not a significant presaccadic N2pc (0.2 μ V), t(23) = 1.53, p = .139, d = 0.31. We also used an alternative measurement window from -100 ms to -10 ms (as in Huber-Huber et al., 2016). A one-sample t test again indicated that the mean amplitude of the difference waveform (0.1 μ V) was not significant, *t*(23) = 1.95, p = .064, d = 0.40. If anything, the nonsignificant trend was in the wrong direction: there was a small contralateral positivity before the first eye movement.

It is possible that the short latency of the first saccade (206 ms) obscured the presaccadic N2pc component. We therefore reexamined the data using only the slowest quartile of saccades from each participant (mean saccadic latency = 251 ms). This should allow enough time to observe the N2pc component (which began at approximately 180 ms in the covert search condition). We still observed no evidence of a presaccadic N2pc component (0.2 μ V difference between contralateral and ipsilateral waveforms), t(23) = 1.52, p = .142, d = 0.31.

Altogether, the results are quite clear: Even though eye movements were strongly guided toward the target stimulus, there was no evidence that these eye



Figure 4. Saccade-locked ERPs from Experiment 1 from the overt search condition. Unlike traditional visually-evoked ERPs, these ERPs were time-locked to the onset of the first saccade. (A) ERP waveforms for electrode sites that are ipsilateral and contralateral to the target. As can be seen, there is no evidence of a presaccadic N2pc before the onset of the first saccade. A histogram of stimulus onsets is plotted beneath this ERP waveform. (B) Difference waveforms created by subtracting ipsilateral waveforms from contralateral waveforms. (C) A series of scalp topography maps averaged over 100 ms intervals. Rather than plotting contralateral minus ipsilateral activity, which forces values to be zero on the midline, these maps show voltages for right-target trials minus left-target trials.

movements were preceded by a presaccadic N2pc component.

2.2.5 Post-Saccadic N2pc Components

As can be seen in Figure 4A, there was an N2pc-like component that occurred after the first saccade (i.e., rightward of the time-lock). But as shown in scalp topography (Figure 4C), this large contralateral voltage largely emanated from the canthi of the eyes rather than occipital electrode sites, indicating a large extraocular artifact (see also Lins et al., 1993). In the Supplemental Materials, we conducted a set of exploratory analyses using independent component analyses (ICA) to remove extraocular artifacts to assess whether there was a post-saccadic N2pc component (Drisdelle et al., 2017). The ICA correction was largely successful at eliminating extraocular artifacts. It also massively reduced the magnitude of the post-saccadic contralateral negativity. There was, however, some limited evidence for a small N2pc following the saccade, which could suggest that an N2pc was generated in parallel with the first eye movement. However, we urge caution in interpretation of this component because it is difficult to determine whether the ICA-based correction truly eliminated all extraocular artifacts (for more on this, see the General Discussion).

2.3 Discussion

In this experiment, participants searched for a target-colored square and manually reported the location of the gap inside (top or bottom). In the covert search condition, eye movements were prohibited. Consistent with many previous studies, we observed a robust N2pc component to the target stimulus (e.g., Woodman & Luck, 1999, 2003). Importantly, in the overt search condition, participants freely generated eye movements during visual search. Approximately 75% of first saccades were directed to the target with an average latency of 206 ms. There was no indication, however, that these saccades were preceded by a presaccadic N2pc component. This suggests that eye movements are not mandatorily preceded by an N2pc component during typical visual search.

3. Experiment 2

In Experiment 1, there was no evidence of a presaccadic N2pc component in the overt search condition. Some previous studies, however, have detected a presaccadic N2pc component (Huber-Huber et al., 2016; Luck et al., 1997; Weaver et al., 2017). This raises the question of why there are discrepant results. One observation is that, in the current study, eye movements were allowed to be generated freely in service of search, with no penalty of directing saccades to distractors. This resulted in rapid saccades that occurred approximately 200 ms poststimulus (see also Beck & Hollingworth, 2017; Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018b; Kruijne & Meeter, 2016; Mulckhuyse et al., 2008; Shurygina et al., 2019; Talcott & Gaspelin, 2020). Previous studies that have observed presaccadic N2pc components, however, have required participants to make eve movements to the target as a response, and participants were penalized for directing gaze to distractors (Huber-Huber et al., 2016; Luck et al., 1997; Weaver et al., 2017). This approach may encourage participants to covertly attend the target stimulus before moving the eves to the target as a



Figure 5. Stimuli and procedure for Experiment 2. Participants searched for a square of a specific color (e.g., green). In the *overt search* condition, participants searched for the target-colored square while making eye movements and made a manual response reporting the location of the gap (top or bottom). Importantly, in the *scout search* condition, participants first searched for the target-colored square using covert attention (blue dashed circle) and generated an eye movement to the target only if the target-colored square had a gap in a certain location. If the gap was in the correct location (e.g., top), participants made an eye movement toward the target as a response (*go trial*). If the gap was in the incorrect location (e.g., bottom), the participants withheld eye movements (*no-go trial*).

response, which may be crucial toward observing a presaccadic N2pc component.

To assess this, Experiment 2 used a similar task to Experiment 1. but with two experimental conditions (Figure 5). The overt search condition was identical to Experiment 1: participants were allowed to freely generate eye movements to find the target square and made a manual response to the location of a gap in the target. Importantly, we introduced a new scout search condition. Participants searched for a square of a specific color (e.g., green) and if this square had a gap at a certain location (e.g., top), participants made an eye movement toward the square as a response (go trial). If the gap was in the incorrect location (e.g., bottom), participants refrained from generating an eye movement (no-go trial). Thus, to accurately perform this condition, participants must covertly attend the target-colored item before generating an eye movement.

In the overt search condition, we expect to replicate the results of Experiment 1: there will be no

presaccadic N2pc component. The key prediction pertains to the new scout search condition. This control condition forces participants to covertly attend the target-colored square before generating an eye movement. If the N2pc component indexes the focusing of covert attention on the target, a presaccadic N2pc component should now be detected. Simply put, this control condition allows us to ensure our experimental approach is sensitive to detect a presaccadic N2pc component.

3.1 Method

All methods were identical to Experiment 1, except for the following changes.

3.1.1 Participants

A new sample of 24 undergraduates (M_{age} = 18.8 years, 16 women and 8 men) were recruited. One participant was replaced for making eye movements on fewer than 75% of trials. Another was replaced because EEG artifacts (eye blinks, high-voltage noise) occurred on more than 25% of trials.

3.1.2 Stimuli and Procedure

The overt search condition was identical to that of Experiment 1. In the new scout search condition, participants searched for the target-colored square and directed eve movements to the target as the response. If the target-colored square had a gap at a specific location (e.g., top), participants made an eye movement to the target stimulus (go trial). If the targetcolored square had a gap in the wrong location (e.g., bottom), they were instructed to refrain from making an eye movement (no-go trial). The scout search condition therefore required participants to use covert attention to carefully inspect the target before generating an eye movement. Each trial type (go vs. no-go) was equally likely. Search stimuli were identical in both overt search and scout search conditions, including the gap size (0.2°).

On go trials, responses were classified as being correct if gaze position entered a region that was within 1.1° of the target square. If gaze entered within 1.1° of the distractor-colored square, the trial ended and an error tone at 200 Hz sounded for 300 ms. On no-go trials, participants were considered to have made an accurate response if gaze remained within 1.5° of central fixation for 1000 ms. If gaze shifted beyond

this radius, the trial immediately ended, and a 200-Hz error tone sounded for 300 ms.

3.1.3 Data analysis

All data analyses were identical to Experiment 1, except as follows. First, epoch windows were elongated to account for the longer saccadic latencies from the scout search condition (M = 566 ms). For stimulus-locked ERPs, we established an 800-ms epoch, beginning 200 ms before the onset of the search array. For saccade-locked ERPs, we established a 700-ms epoch window that began 500 ms before the first saccade in the overt search condition. Again, because saccades were slowed in the scout search condition, this condition used a slightly larger epoch window that began 800 ms before the first saccade.

Trials were excluded from analysis if they contained an incorrect response (0.6%) or an abnormal manual RT (less than 200 ms or greater than 1500 ms; 0.3%). Trials with an abnormal saccadic latency were also excluded (less than 50 ms or greater than 1000 ms; 0.6%). Additionally, trials were excluded from EEG analyses if they did not contain a saccade in the overt search condition (6.3%) and on go trials of the scout search condition (4.1%). Trials were excluded from EEG analysis of no-go trials in the scout search condition if they did contain an eye movement (8.9%).

3.2 Results

3.2.1 Manual RT and Error Rates

In the overt search condition, the mean RT of the manual response was 657 ms, and the mean error rate was 1.1%. In the scout search condition, no manual responses were required.

3.2.2 First Saccade Destination and Latency

Figure 6A depicts heat maps of first saccade destinations for the overt search condition and go trials in the scout search condition. Figure 6B depicts percentage of eye movements to the target-colored item and distractor-colored item in overt and scout search conditions. In both conditions, first eye movements were highly likely to be directed to the target-colored square.

In overt search blocks, first saccades were more



Figure 6. Eye movement results from Experiment 2. (A) Heat maps of first saccade destination on trials where the target appeared on the left or right location for the scout search condition (go trials only) and overt search condition. (B) Percentage of first saccades to the target and distractor item collapsed across both target locations in the scout search condition (go-trials only) and the overt search condition.

likely to be directed to the target-colored square (86.9%) than the distractor-colored square (13.1%), t(23) = 14.57, p < .001, $d_z = 2.97$. In scout search blocks (go trials only), almost every trial contained a first saccade directed to the target-colored square (99.0%) rather than to the distractor-colored square (0.2%), t(23) = 304.0, p < .001, $d_z = 62.1$. We also compared the percentage of first saccades to the target between conditions. First saccades were more likely to be directed to the target on go trials of scout search blocks (99.0%) than overt search blocks (86.9%), t(23) = 4.70, p < .001, d = 0.96.

It is important to highlight that, in the scout search condition, there were also trials where participants refrained from generating eye movements (no-go trials). Table 1 depicts saccadic performance relative to each trial type (go vs. no-go) in scout search blocks. The false alarm rate—calculated as the percentage of no-go trials with a saccade generated to the targetcolored square when the gap was in the wrong location—was 8.6%. The miss rate on go trials (i.e., the percentage of go trials with a withheld saccade) was 0.8%. Thus, participants were more willing to accidentally direct a saccade to the target-colored foil on a no-go trial than miss directing a saccade to the target on go trials.

We also computed first saccade latency in the overt search blocks and go trials of scout search blocks. Latencies of saccades directed to the target were slower on scout search blocks (566 ms) than on overt search blocks (221 ms), t(23) = 31.88, p < .001, $d_z = 6.51$. This indicates that participants carefully inspected the potential target before initiating a saccade in the scout condition, but not the overt condition (for more, see below).

3.2.3 Stimulus-Locked ERPs

Figure 7 depicts the stimulus-locked ERPs in overt search and scout search conditions. Recall that the scout search condition had two types of trials, go trials (eye movement to target) and no-go trials (eye movement withheld), which are depicted in Figure 7A and 7C, respectively. Figure 7B depicts stimuluslocked ERPs in the overt search condition. In all conditions, there was an N2pc-like contralateral

Table 1 Exist second destination (0/) by second item on no. so trials for Experiment 2

First saccade destination (%) by search item on no-go trials for Experiment 2			
	Target Color	Distractor Color	Fixation
Go Trials	99.0 (0.3)	0.2 (0.1)	0.8 (0.3)
No-Go Trials	8.6 (1.2)	0.3 (0.1)	91.1 (1.2)

Note. Numbers in parentheses indicate standard error of the mean.



Figure 7. Stimulus-locked ERPs from Experiment 2. (A), (B), and (C) depict ERP waveforms for electrode sites that are ipsilateral and contralateral to the target-colored item. Because no eye movements were generated on no-go trials of the scout condition (panel C), any lateralized ERP activity between 200–300 ms should reflect covert attentional selection that is uncontaminated by oculomuscular artifacts. Difference waveforms (panel D) were created by subtracting ipsilateral waveforms from contralateral waveforms.

negativity from approximately 200–300 ms poststimulus. The mean amplitudes of the N2pc-like component are highly significant in all of the conditions: the overt search condition (-1.3 μ V), t(23) = 5.83, p < .001, d = 1.19, the go-trials of the scout search condition (-0.5 μ V), t(23) = 3.73, p = .001, d = 0.76, and the no-go trials of the scout search condition

 $(-0.5 \ \mu\text{V}), t(23) = 4.13, p < .001, d = 0.84.$

As in Experiment 1, the stimulus-locked N2pc components are difficult to interpret because they are contaminated by artifactual voltages that arise from eye movements. The one exception is the no-go trials of the scout search condition. On these trials, a target-colored square had a gap in the wrong location (a

target foil) and participants refrained from making eye movements. These trials provide some preliminary evidence that covert attention was allocated to the target before the first eye movement in this condition. If participants covertly discriminated the target-colored item before deciding whether to generate a saccade, there should be an N2pc component even on trials where they did not generate a saccade. Indeed, there was an N2pc component in this condition. Although compelling, these trials do not directly indicate that a shift of covert attention was made before the first eye movement in the scout condition. In the next section, we will address this by time-locking the ERP components to the onset of the first saccade in the overt search condition and go-trials of the scout search condition.



Figure 8. Saccade-locked ERPs from Experiment 2. (A) and (B) ERP waveforms for electrode sites that are ipsilateral and contralateral to the target in the scout search condition and overt search condition. The average stimulus onset is shown as a vertical line, and histograms for stimulus onset are shown below these ERP waveforms. (C) Difference waveforms were created by subtracting ipsilateral waveforms from contralateral waveforms. (D) Scalp topography maps averaged over 100 ms intervals are shown for scout search and overt search conditions.

3.2.4 Saccade-Locked ERPs

Saccade-locked ERP waveforms for scout search blocks and overt search blocks are depicted in Figure 8A and 8B, respectively. Contra-minus-ipsi difference waveforms for both conditions are depicted in Figure 8C. Figure 8D depicts scalp topography maps averaged in 100 ms intervals for right-target trials minus left-target trials.

The key question is whether a presaccadic N2pc was detectable in the scout search condition, which forced participants to covertly attend the target stimulus prior to initiating a saccade. If the current approach is at all sensitive to detect a presaccadic N2pc component, it should be apparent in this condition. As shown in Figure 8A, there is clear contralateral negativity before the onset of the first saccade. This presaccadic N2pc is sustained, which is likely due to the broad distribution of saccadic latencies, as depicted in the histogram of stimulus onset times below the waveform. Using a time window of -50 to 0 ms, the mean amplitude of the contraminus-ipsi difference waveform (-0.7 µV) was significantly less than zero, t(23) = 3.13, p = .005, d =0.64. Using an alternative time window of -100 to -10 ms, the mean amplitude of the difference waveform (-0.7 μ V) is also highly significant, t(23) = 3.13, p = .005, d = 0.64. In short, there was a clear presaccadic N2pc component on the go-trials of the scout search condition.

In the overt search condition (Figure 8B), there was no evidence of a presaccadic N2pc, just as in Experiment 1. The mean amplitude of the contraminus-ipsi difference waveform was not statistically significant from -50 to 0 ms (0.1 μ V), t(23) = 0.96, p =.347, d = 0.20, nor from -100 to -10 ms (0.0 μ V), t(23)= 0.31, p = .757, d = 0.06. We also compared the magnitude of the presaccadic N2pc between the scout search condition and overt search condition. From -50 to 0 ms, the magnitude of the presaccadic N2pc was much larger in the scout search condition (-0.7 µV) than the overt search condition (0.1 μ V), t(23) = 3.48, p =.002, $d_z = 0.71$. Using the alternate time window of -100 to -10 ms, the presaccadic N2pc was still larger in the scout search condition (-0.7 µV) than in the overt search condition (0.0 μ V), t(23) = 2.72, p = .012, $d_z =$ 0.56.

The scalp topography maps (Figure 8D) clearly indicate that the presaccadic N2pc component in the scout search condition resulted primarily from

posterior electrode sites, consistent with previous studies of the N2pc component (Eimer, 1996; Gaspelin & Luck, 2018a; Hickey et al., 2009; Huber-Huber et al., 2016; Luck & Hillyard, 1994b; Tan & Wyble, 2015; Weaver et al., 2017; Woodman & Luck, 1999). No such presaccadic lateralized negativity is present in the posterior sites in the overt search condition. Instead, there were only large voltage artifacts from the eye movements after the first eye movement.

Altogether, these results suggest that, in the overt search condition, eye movements were rapidly directed to the target-colored square without a presaccadic N2pc component. In the scout search condition, participants were forced to covertly attend the target before initiating an eye movement toward the targetcolored square. This yielded slower eye movements with a clear presaccadic N2pc component.

3.2.5 Post-Saccadic N2pc

In the Supplemental Materials, we conducted an exploratory analysis to assess whether first saccades in the overt search condition were followed by an N2pc component. We used ICA-based approaches to remove extraocular artifacts from the EEG signal (Drisdelle et al., 2017). As a result of the ICA, the contralateral negativity after the first saccade was massively reduced, but still remained. This post-saccadic N2pc component suggests that the N2pc component may be generated in parallel with the initiation of the first eye movement. However, we urge some caution in interpreting this effect because it is unclear if the ICAbased corrective procedure can actually remove all extraocular artifacts. Any remnant extraocular artifact would cause an N2pc-like component (e.g., see scalp topography maps in Figure 8D).

3.3 Discussion

Experiment 2 assessed whether forcing participants to covertly attend the target stimulus before generating an eye movement would result in a presaccadic N2pc component (as in Huber-Huber et al., 2016; Weaver et al., 2017). In the overt search condition, participants freely generated eye movements in service of visual search. This resulted in no presaccadic N2pc component, just as in Experiment 1. In the new scout search condition, participants were required to covertly attend the target-colored square before generating an eye movement as a response. Crucially, there was a robust presaccadic N2pc component. These findings suggest that the N2pc component can sometimes precede eye movements, but only in experimental tasks that encourage participants to covertly attend the target before generating an eye movement.

4. General Discussion

Researchers have long questioned the relationship between covert and overt attention (Klein, 1980; Luck, 2009; Posner, 1980; Remington, 1980). А commonplace assumption is that eye movements are mandatorily preceded by covert attentional selection (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995). That is, covert attention acts as a scout by inspecting potential targets before an eye movement is initiated. However, it is currently unknown whether the N2pc component-a putative index of covert attentional allocation-automatically occurs before every eye movement. Most previous studies of the N2pc component have prohibited eye movements because they cause large voltage artifacts that complicate the interpretation of the N2pc (e.g., Eimer, 1996; Gaspelin & Luck, 2018a; Hickey et al., 2009: Woodman & Luck, 1999, 2003). Although some recent studies have found evidence of presaccadic N2pc components that occur before eye movements (Huber-Huber et al., 2016; Weaver et al., 2017), all of these studies used experimental paradigms that encouraged participants to covertly inspect search items before initiating an eye movement as a response. It is therefore unclear whether eye movements that are naturally generated during visual search are typically preceded by an N2pc component. The current study directly assessed this question.

In Experiment 1, participants searched for a target square of a specific color (e.g., green) and reported the location of a gap inside via manual buttonpress (Woodman & Luck, 1999). In the covert search condition, eye movements were prohibited and there was a large N2pc component similar to those found in many previous studies (Eimer, 1996; Gaspelin & Luck, 2018a; Hickey et al., 2009; Luck & Hillyard, 1994b; Tan & Wyble, 2015; Woodman & Luck, 1999, 2003). In the overt search condition, eye movements were allowed to be freely generated while searching for the target. At analysis, ERP waveforms were time-locked to the onset of the first saccade and neural activity before the first saccade was assessed. There was no evidence of a presaccadic N2pc component that preceded the first eve movement, even though the eves were strongly guided to the target.

Experiment 2 examined how task demands can influence whether covert attention is deployed before eye movements. The overt search condition was identical to Experiment 1 in that participants freely generated eve movements to locate the target and made a manual response once it was located. As in Experiment 1, there was no evidence of a presaccadic N2pc component. Importantly, we introduced a new scout search condition which forced participants to covertly attend the target before generating an eye movement as a response. This condition yielded a robust presaccadic N2pc component, replicating previous studies using saccade-to-target paradigms (Huber-Huber et al., 2016; Luck et al., 1997; Weaver et al., 2017). Altogether, these results suggest the N2pc component will sometimes occur before eve

movement. The current study raises the question of whether eye movements can occur without a preceding shift of covert attention. In the overt search condition of Experiment 1 and 2, first eye movements were strongly guided toward the target stimulus by approximately 200 ms, even though there was no evidence of a preceding N2pc component. One possibility is that eye movements, like covert attention, can be directly guided by preattentive featural information. Many models of attention propose that the visual system automatically generates representative maps of basic stimulus features (e.g., color, line orientation, shape) in the visual field, and that these preattentive feature maps can be used to guide covert attention toward task-relevant objects (Treisman & Gelade, 1980; Wolfe, 2021; Wolfe & Horowitz, 2017). It seems plausible that preattentive feature maps could also be used to directly guide the oculomotor system, at least under certain conditions. This could explain how participants were able to rapidly guide eye movements toward the target-colored square in the overt search condition without any indication of a preceding shift of covert attention.

movements, but only when the task strongly

encourages covert attentional shifts before the eve

In line with the above account, there is some circumstantial evidence suggesting that shifts of covert attention may not be required to locate items defined by simple features. For example, Luck and Ford (1998) found that shifts of covert attention, as indexed by the N2pc component, were greatly diminished when participants searched for a target defined by a simple color compared to a target defined by a color-orientation conjunction (Luck & Hillyard, 1994,

Experiment 2). Additionally, homologues of the N2pc component have been observed before eye movements in nonhuman primates in search tasks where the target is defined as a conjunction (Woodman et al., 2007; Woodman, 2012). Together with the current study, these findings hint that eye movements may only be preceded by covert attentional shifts during search for conjunctive targets, but further research is needed to definitively assess this hypothesis.

It is important to highlight that covert attention is not a unitary phenomenon (Luck & Vecera, 2002), and the N2pc component may index one of many potential cognitive mechanisms involved in attentional selection. Previous research has suggested that the N2pc component may specifically measure cognitive processes such as target localization before a covert shift (Tan & Wyble, 2015), rejection of distractors around the attended item (Hickey et al., 2009; Luck, 2012; Luck & Hillyard, 1994b), object individuation (Foster et al., 2020), or attentional engagement on the target (Zivony et al., 2018). In any case, it is clear from the current study that the specific mechanism of covert attention indexed by the N2pc component does not necessarily precede overt eye movements. The current study may be taken as evidence that contributes to the growing consensus that the N2pc component indexes a relatively late attentional process that occurs after low-level feature extraction (Foster et al., 2020; Woodman & Luck, 2003). Future studies may focus on whether ERP components purported to measure early stages of attentional selection, such as the P1 and N1 (Mangun, 1995; Van Voorhis & Hillyard, 1977), occur before overt eye movements during visual search.

In both experiments in the current study, there was some evidence of a post-saccadic N2pc component that occurred after the first eve movement. In the Supplemental Materials, we demonstrated that even when the EEG signal was ICA corrected to remove eye movement artifacts, there was still a small contralateral negativity immediately following the eye movement. This could indicate that the visual system executes a shift of covert attention in parallel with an eye movement to a search item. Such an approach would be beneficial because the oculomotor system would not need to wait for covert attentional discrimination, which may be relatively slow. However, we urge some caution in interpreting the post-saccadic N2pc component. Our ICA approaches (based upon Drisdelle et al., 2017) may not have entirely eliminated extraocular artifacts. These extraocular artifacts can

cause ERP components that look very similar to an N2pc but are actually generated by voltage dipoles from the retina (i.e., a corneoretinal potential; Lins et al., 1993). Simply put, future studies are needed to definitively determine whether shifts of covert attention can be executed in parallel with eye movements.

It is worth noting a potential relationship between the short-latency saccades in the current study and express saccades. In humans, express saccades are rapid eye movements (ca. 80-120 ms) that occur when the fixation stimulus is removed prior to the onset of the target stimulus (Fischer & Weber, 1993; Kingstone & Klein, 1993). Although the current study was not designed to induce express saccades (i.e., the fixation cross was not removed prior to stimulus presentation), the saccades observed in the overt search conditions were quite fast (ca. 200 ms). To be fair, these short-latency saccades are consistent with previous studies of naturalistic saccades in visual search tasks (ca. 175-225 ms; Beck & Hollingworth, 2017; Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018b; Henderson, 2003; Kruijne & Meeter, 2016; Mulckhuyse et al., 2008; Shurygina et al., 2019; Talcott & Gaspelin, 2020). Nonetheless, it is possible that some aspect of the current design (e.g., the simple color discrimination) caused unusually fast saccades that did not need to be preceded by shifts of covert Future research may therefore explore attention. whether express saccades are typically preceded by shifts of covert attention using concurrent EEG and eve-tracking.

In summary, the current study demonstrates that naturalistic eye movements during visual search are not always preceded by an N2pc component. This suggests that the covert attentional process indexed by the N2pc component does not automatically occur movements. This has before eve important implications for basic science models of oculomotor control and visual search more broadly. It also has an important practical implication for future studies that concurrently measure eye movements and EEG: The presaccadic N2pc component will occur before eve movements only if the experimental task strongly encourages a shift of covert attention before an eye movement is generated.

Appendix A. Supplemental Material

Supplemental data to this article can be accessed online at [link not yet available].

The original data, data analysis programs, and

stimulus presentation programs are available on the Open Sciences Framework at: <u>https://osf.io/8wkas/?view_only=fb9ab2daebe64909b30c3437d77430e6</u>.

References

- Beauchamp, M. S., Petit, L., Ellmore, T. M., Ingeholm, J., & Haxby, J. V. (2001). A parametric fMRI study of overt and covert shifts of visuospatial attention. Neuroimage, 14(2), 310–321.
- Beck, V. M., & Hollingworth, A. (2017). Competition in saccade target selection reveals attentional guidance by simultaneously active working memory representations. Journal of Experimental Psychology: Human Perception and Performance, 43(2), 225.
- Bell, A. J., & Sejnowski, T. J. (1997). The "independent components" of natural scenes are edge filters. Vision Research, 37(23), 3327–3338.
- Brainard, D. H. (1997). The psychophysics toolbox. Spatial Vision, 10, 433–436.
- Chelazzi, L., Duncan, J., Miller, E. K., & Desimone, R. (1998). Responses of neurons in inferior temporal cortex during memory-guided visual search. Journal of Neurophysiology, 80(6), 2918–2940.
- Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The Eyelink Toolbox: Eye tracking with MATLAB and the Psychophysics Toolbox. Behavior Research Methods, Instruments, & Computers, 34(4), 613– 617.
- Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. Journal of Neuroscience Methods, 134(1), 9–21.
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. Vision Research, 36(12), 1827–1837.
- Dimigen, O., Sommer, W., Hohlfeld, A., Jacobs, A. M., & Kliegl, R. (2011). Coregistration of eye movements and EEG in natural reading: Analyses and review. Journal of Experimental Psychology: General, 140(4), 552.
- Drisdelle, B. L., Aubin, S., & Jolicoeur, P. (2017). Dealing with ocular artifacts on lateralized ERPs in studies of visual-spatial attention and memory: ICA correction versus epoch rejection. Psychophysiology, 54(1), 83–99.

- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. Electroencephalography and Clinical Neurophysiology, 99(3), 225–234.
- Fischer, B., & Weber, H. (1993). Express saccades and visual attention. Behavioral and Brain Sciences, 16(3), 553–567.
- Foster, J. J., Bsales, E. M., & Awh, E. (2020). Covert spatial attention speeds target individuation. Journal of Neuroscience, 40(13), 2717–2726.
- Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. Journal of Neuroscience, 34(16), 5658–5666.
- Gaspelin, N., Gaspar, J. M., & Luck, S. J. (2019). Oculomotor inhibition of salient distractors: Voluntary inhibition cannot override selection history. Visual Cognition, 1–20.
- Gaspelin, N., Leonard, C. J., & Luck, S. J. (2017). Suppression of overt attentional capture by salientbut-irrelevant color singletons. Attention, Perception, & Psychophysics, 79(1), 45–62.
- Gaspelin, N., & Luck, S. J. (2018a). Combined electrophysiological and behavioral evidence for the suppression of salient distractors. Journal of Cognitive Neuroscience, 30(9), 1265–1280.
- Gaspelin, N., & Luck, S. J. (2018b). Distinguishing among potential mechanisms of singleton suppression. Journal of Experimental Psychology: Human Perception and Performance, 44(4), 626.
- Henderson, J. M. (2003). Human gaze control during real-world scene perception. Trends in Cognitive Sciences, 7(11), 498–504. https://doi.org/10.1016/j.tics.2003.09.006
- Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. Journal of Cognitive Neuroscience, 21(4), 760–775.
- Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. Perception & Psychophysics, 57(6), 787–795.
- Horowitz, T. S., Wolfe, J. M., Alvarez, G. A., Cohen, M. A., & Kuzmova, Y. I. (2009). The speed of free will. The Quarterly Journal of Experimental Psychology, 62(11), 2262–2288.
- Huber-Huber, C., Ditye, T., Fernández, M. M., & Ansorge, U. (2016). Using temporally aligned eventrelated potentials for the investigation of attention shifts prior to and during saccades. Neuropsychologia, 92, 129–141.
- Irwin, D. E., & Gordon, R. D. (1998). Eye movements, attention and trans-saccadic memory. Visual Cognition, 5(1–2), 127–155.

- Kastner, S., & Ungerleider, L. (2000). Mechanisms of visual attention in the human cortex. Annual Review of Neuroscience, 23(1), 315–341.
- Khan, A. Z., Song, J.-H., & McPeek, R. M. (2011). The eye dominates in guiding attention during simultaneous eye and hand movements. Journal of Vision, 11(1), 9–9.
- Kingstone, A., & Klein, R. M. (1993). What are human express saccades? Perception & Psychophysics, 54(2), 260–273.
- Kiss, M., Van Velzen, J., & Eimer, M. (2008). The N2pc component and its links to attention shifts and spatially selective visual processing. Psychophysiology, 45(2), 240–249.
- Klein, R. M. (1980). Does Oculomotor Readiness Mediate Cognitive Control of Visual Attention? Attention and Performance VIII, 8, 259.
- Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. Vision Research, 35(13), 1897–1916.
- Krebs, R. M., Boehler, C. N., Zhang, H. H., Schoenfeld, M. A., & Woldorff, M. G. (2012). Electrophysiological recordings in humans reveal reduced locationspecific attentional-shift activity prior to recentering saccades. Journal of Neurophysiology, 107(5), 1393–1402.
- Kruijne, W., & Meeter, M. (2016). Implicit short-and long-term memory direct our gaze in visual search. Attention, Perception, & Psychophysics, 78(3), 761–773.
- Lins, O. G., Picton, T. W., Berg, P., & Scherg, M. (1993). Ocular artifacts in EEG and event-related potentials I: Scalp topography. Brain Topography, 6(1), 51–63.
- Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. Frontiers in Human Neuroscience, 8, 213.
- Luck, S. J. (2009). The spatiotemporal dynamics of visual-spatial attention. In From Attention to Goal-Directed Behavior (pp. 51–66). Springer.
- Luck, S. J. (2012). Electrophysiological correlates of the focusing of attention within complex visual scenes: N2pc and related ERP components. The Oxford Handbook of Event-Related Potential Components, 329–360.
- Luck, S. J., & Ford, M. A. (1998). On the role of selective attention in visual perception. Proceedings of the National Academy of Sciences, 95(3), 825–830.

- Luck, S. J., & Gaspelin, N. (2017). How to get statistically significant effects in any ERP experiment (and why you shouldn't). Psychophysiology, 54(1), 146–157.
- Luck, S. J., Girelli, M., McDermott, M. T., & Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. Cognitive Psychology, 33(1), 64–87.
- Luck, S. J., & Hillyard, S. A. (1994a). Electrophysiological correlates of feature analysis during visual search. Psychophysiology, 31(3), 291– 308.
- Luck, S. J., & Hillyard, S. A. (1994b). Spatial filtering during visual search: Evidence from human electrophysiology. Journal of Experimental Psychology: Human Perception and Performance, 20(5), 1000–1014. https://doi.org/10.1037/0096-1523.20.5.1000
- Luck, S. J., & Vecera, S. P. (2002). Attention. In H. Pashler & S. Yantis (Eds.), Steven's handbook of experimental psychology: Sensation and perception., Vol. 1, 3rd ed. (2002-01034-006; pp. 235-286). John Wiley & Sons Inc; APA PsycInfo. http://proxy.binghamton.edu/login?url=https://se arch.ebscohost.com/login.aspx?direct=true&db=ps yh&AN=2002-01034-006&site=ehost-live
- Mangun, G. R. (1995). Neural mechanisms of visual selective attention. Psychophysiology, 32(1), 4–18.
- Mazza, V., Turatto, M., & Caramazza, A. (2009a). An electrophysiological assessment of distractor suppression in visual search tasks. Psychophysiology, 46(4), 771–775.
- Mazza, V., Turatto, M., & Caramazza, A. (2009b). Attention selection, distractor suppression and N2pc. Cortex, 45(7), 879–890.
- Moore, T., & Fallah, M. (2001). Control of eye movements and spatial attention. Proceedings of the National Academy of Sciences, 98(3), 1273– 1276.
- Moore, T., & Fallah, M. (2004). Microstimulation of the frontal eye field and its effects on covert spatial attention. Journal of Neurophysiology, 91(1), 152–162.
- Mulckhuyse, M., van Zoest, W., & Theeuwes, J. (2008). Capture of the eyes by relevant and irrelevant onsets. Experimental Brain Research, 186(2), 225– 235.

- Plöchl, M., Ossandón, J. P., & König, P. (2012). Combining EEG and eye tracking: Identification, characterization, and correction of eye movement artifacts in electroencephalographic data. Frontiers in Human Neuroscience, 6, 278.
- Posner, M. I. (1980). Orienting of attention. Quarterly Journal of Experimental Psychology, 32(1), 3–25.
- Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. The Quarterly Journal of Experimental Psychology, 62(8), 1457–1506.
- Remington, R. W. (1980). Attention and saccadic eye movements. Journal of Experimental Psychology: Human Perception and Performance, 6(4), 726.
- Rolfs, M., Jonikaitis, D., Deubel, H., & Cavanagh, P. (2011). Predictive remapping of attention across eye movements. Nature Neuroscience, 14(2), 252–256.
- Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A common neural mechanism for preventing and terminating the allocation of attention. The Journal of Neuroscience, 32(31), 10725–10736.
- Schall, J. D., & Thompson, K. G. (1999). Neural selection and control of visually guided eye movements. Annual Review of Neuroscience, 22(1), 241–259.
- Shurygina, O., Kristjánsson, Á., Tudge, L., & Chetverikov, A. (2019). Expectations and perceptual priming in a visual search task: Evidence from eye movements and behavior. Journal of Experimental Psychology: Human Perception and Performance, 45(4), 489.
- Smith, T. J., & Henderson, J. M. (2011). Does oculomotor inhibition of return influence fixation probability during scene search? Attention, Perception, & Psychophysics, 73(8), 2384–2398.
- Talcott, T. N., & Gaspelin, N. (2020). Prior target locations attract overt attention during search. Cognition, 201, 104282.
- Tan, M., & Wyble, B. (2015). Understanding how visual attention locks on to a location: Toward a computational model of the N2pc component. Psychophysiology, 52(2), 199–213.
- Theeuwes, J., Kramer, A. F., Hahn, S., & Irwin, D. E. (1998). Our eyes do not always go where we want them to go: Capture of the eyes by new objects. Psychological Science, 9(5), 379–385.
- Thickbroom, G. W., & Mastaglia, F. L. (1986). Presaccadic spike potential. Relation to eye movement direction. Electroencephalography and Clinical Neurophysiology, 64(3), 211–214.

- Treisman, A. M., & Gelade, G. (1980). A featureintegration theory of attention. Cognitive Psychology, 12(1), 97–136.
- Van Voorhis, S., & Hillyard, S. A. (1977). Visual evoked potentials and selective attention to points in space. Perception & Psychophysics, 22(1), 54–62.
- van Zoest, W., Donk, M., & Theeuwes, J. (2004). The role of stimulus-driven and goal-driven control in saccadic visual selection. Journal of Experimental Psychology: Human Perception and Performance, 30(4), 746.
- Weaver, M. D., van Zoest, W., & Hickey, C. (2017). A temporal dependency account of attentional inhibition in oculomotor control. NeuroImage, 147, 880–894.
- Wolfe, J. M. (2020). Visual Search: How Do We Find What We Are Looking For? Annual Review of Vision Science, 6.
- Wolfe, J. M. (2021). Guided Search 6.0: An updated model of visual search. Psychonomic Bulletin & Review, 1–33.
- Wolfe, J. M., & Horowitz, T. S. (2017). Five factors that guide attention in visual search. Nature Human Behaviour, 1(3), 0058.
- Woodman, G. F. (2012). Homologues of human ERP components in nonhuman primates. Oxford Handbook of Event-Related Potential Components, 1st Edn. Oxford University Press, New York, 611– 626.
- Woodman, G. F., Kang, M.-S., Rossi, A. F., & Schall, J. D. (2007). Nonhuman primate event-related potentials indexing covert shifts of attention. Proceedings of the National Academy of Sciences, 104(38), 15111–15116.
- Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. Nature, 400(6747), 867.
- Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. Journal of Experimental Psychology: Human Perception and Performance, 29(1), 121–138. psyh. https://doi.org/10.1037/0096-1523.29.1.121
- Wu, S.-C., & Remington, R. W. (2003). Characteristics of covert and overt visual orienting: Evidence from attentional and oculomotor capture. Journal of Experimental Psychology: Human Perception and Performance, 29(5), 1050–1067.

Zivony, A., Allon, A. S., Luria, R., & Lamy, D. (2018). Dissociating between the N2pc and attentional shifting: An attentional blink study. Neuropsychologia, 121, 153–163.

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