Effects of Spatial Attention on Visuocortical Processing: A Multi-Laboratory Replication of Clark & Hillyard (1996)

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Abstract

Whether selective attention alters initial sensory processing or instead only operates at higher cortical stages (often referred to as early vs. late selection) is a foundational question in cognitive neuroscience. Investigating the influence of covert visual selective attention, Clark and Hillyard (1996) found that directed attention modulated the amplitude of several early components (P1 and N1) of the visual event-related potential (ERP) derived from the ongoing electroencephalogram (EEG). However, attended and non-attended visual stimuli did not produce statistically different amplitudes in the C1 or P2 components. Dipole source estimation of the neural locus of these ERPs indicated that the C1 originated in primary (striate) visual cortex (V1), while the later components primarily arose from extrastriate visuocortical areas. Together, these results led to the conclusion that sustained spatial attention enhances the sensory gain of early visual processing in V1 via feedback projections from the extrastriate visual cortex where the P1 and N1 are generated. Despite the influential nature of this original work in EEG and cognitive neuroscience more broadly, recent research has reignited the debate on which stage of the visual processing hierarchy is influenced by attention. As part of the #EEGManyLabs project (Pavlov et al., 2021), we will be revisiting this issue by conducting a multi-site, high-powered direct replication of Clark and Hillyard (1996).

Keywords: ERP, attention, C1, P1, N1, replication

Effects of Spatial Attention on Visuocortical Processing: Replication of Clark & Hillyard (1996)

Visual selective attention facilitates the processing of behaviorally relevant items and/or locations within the visual field at the cost of less immediately important aspects(Buschman & Kastner, 2015; Posner, 1980; reviewed in Fiebelkorn & Kastner, 2020). Research using event-related potentials (ERPs) has been crucial in testing competing theories of selective attention. In a seminal study, Clark and Hillyard (1996) reported that covertly (i.e. without eye movement, as inferred from the EOG channel) directing attention to laterally presented checkerboard pattern stimuli resulted in enhanced amplitudes in the P1 and N1 ERP components but did not alter the amplitude of the earlier C1 component. Although the precise neuroanatomical mapping of visual areas to ERP components is still debated (e.g., Ales et al., 2013), it is now widely accepted that primary (striate) visual cortex (V1) contributes to the generation of the C1, especially to its early portion, and that subsequent ERP components (P1 and N1) originate primarily in extra-striate regions. Some of the evidence supporting V1 contributions comes from careful combination of psychophysics and C1 recordings, isolating eye-selective, orientation-selective, and location-selective neurons, which rarely occur outside V1 in humans (Thigpen, 2017). The findings in Clark and Hillyard (1996) supported theories positing spatial selective attention as an early mechanism of sensory gain that alters post-V1 cortical processing of lateralized stimuli. These findings, along with numerous corroborating ERP studies of selective attention, largely settled the "early versus late" locus of attention debate (in favor of the former) previously occupying experimental psychology. However, work subsequent to Clark and Hillyard (1996) has continued to examine the neural and experimental factors that modulate the C1, P1, and N1 ERP components. For example, a recent special issue examined the experimental manipulations that

may contribute to attentional modulation of the C1 specifically (Slotnick, 2018). This and other work has suggested that visual field location, presence of cues and distractors, and other factors such as observer expectancy and trial blocking affect the extent to which attention effects on the C1 are seen in a given study (see Slotnick, 2020 for a review of this literature).

Recently, the debate regarding the earliest component modulated by spatial attention has been rekindled by several reports observing C1 modulation in a variety of attention tasks, including spatial attention. Whether attention alters initial sensory processing or instead only operates at higher cortical stages (i.e. early vs. late selection) is a fundamental question in cognitive neuroscience (reviewed in Driver, 2001). Late selection accounts of attention hold that the majority of visual stimulus processing proceeds pre-attentively, with attention selecting from amongst finished perceptual products (Deutsch & Deutsch, 1963). Early selection, on the other hand, proposes that attention operates as a filter and is required for a visual stimulus to receive anything beyond the most rudimentary processing (Broadbent, 1982; Lachter et al., 2004). It is now widely accepted that selective attention affects early processes, but there is ongoing debate regarding the underlying dynamics (Buschman & Kastner, 2015). This includes questions regarding the stages of visual processing that are affected by different types of selective attention (Zhang & Luck, 2009). The C1, P1, and N1 are all characteristic of the short latency ("early") visual ERP, and their amplitude modulation is considered to reflect early selection processes (Luck et al., 2000). Measured from occipital sensor locations, typical peak voltage deflections for the C1 generally occur at 50–90 ms following stimulus onset, followed by the P1 (80–130 ms), and N1 (140–200 ms; Hillyard & Anllo-Vento, 1998; Luck, 2014). These three components are often termed *exogenous*, as they are reliably triggered by the presence of a visual stimulus regardless of task or internal state (Luck & Kappenman, 2011). Directing selective attention

however tends to increase the amplitudes of the P1 and N1 components, an effect referred to as gain control or amplification (Humphreys et al., 1998; Mangun, 1995). Gain control effects upon the P1-N1 complex, as reported in Clark and Hillyard (1996), thus supports the early selection account of attentional selection, even though the earliest (C1) component arising from V1 was not modulated by directed spatial attention.

Numerous efforts have demonstrated that, under certain experimental conditions, covert spatial attention manipulations produce no statistical differences in the C1 component of the ERP compared to non-attended stimuli (Baumgartner et al., 2018; Hillyard & Anllo-Vento, 1998; reviewed in Luck et al., 2000). This has led some researchers (e.g., Baumgartner et al., 2018) to suggest that the effects of spatial attention on event-related visual stimulus processing first manifest with the P1 in extrastriate visual cortex, while the C1 is unaffected by spatial attention (e.g., Aine et al., 1995; Ding et al., 2014; Martinez et al., 1999).

An important point of emphasis is that results reported in Clark and Hillyard (1996) pertain specifically to the impact of attentional manipulations upon the visual ERP, which reflects transient, sensory-evoked processing (Hillyard et al., 1998). Given the highly uncertain nature of estimating cortical source information from scalp-recorded voltages (Hillyard et al., 1998; Luck et al., 2000), imaging modalities with better spatial resolution have also been incorporated to probe the sources of attention effects in vision. Several positron emission tomography (PET; e.g., Corbetta et al., 1990) and combined PET-ERP (Heinze et al., 1994; Mangun et al., 1997) studies have, like most early ERP-only studies, found that spatial attention first modulates processing of sensory information in extrastriate areas of the ventral visual pathway. More recently, numerous functional magnetic resonance imaging (fMRI) investigations have shown attention effects in primary visual cortex (Brefczynski & DeYoe, 1999; Gandhi et

al., 1999; Kanwisher & Wojciulik, 2000; Somers et al., 1999; reviewed in Carrasco, 2011 and Kanwisher & Wojciulik, 2000), as well as in lateral geniculate nucleus (LGN; O'Connor et al., 2002; Schneider & Kastner, 2009), which directly precedes V1 in the visual processing hierarchy. Due to the low temporal resolution of fMRI, attention effects observed in V1 may reflect feedback from higher cortical areas, with the initial feedforward sensory response thought to be indexed by the C1 remaining unaffected (Luck et al., 2000; Martinez et al., 1999). Collecting both fMRI and ERP responses to the same experimental stimuli has demonstrated that visual attention can increase BOLD activity in V1 without modulating the C1 waveform (Martinez et al., 1999; Noesselt et al., 2002) bolstering the feedback hypothesis. Neuroimaging evidence of attention modulation of V1 therefore does not necessarily contradict results from C1 studies finding null effects of attention manipulations.

Distinguishing between feed-forward and feed-back signals, however, cannot explain all discrepancies in the literature, as several studies have reported attention-related modulation of the C1 (Fu et al., 2009; Herde et al., 2022; Karns & Knight, 2009; Kelly et al., 2008; Poghosyan & Ioannides, 2008; Rauss et al., 2009; Wolf et al., 2022; reviewed in Rauss et al., 2011; Qin et al., 2022). One of the first studies to suggest that the C1 is altered by selective attention (Kelly et al., 2008) employed an individual-subject functional localizing procedure to find onscreen presentation locations that produced optimal C1 responses. The pronounced C1 enhancement with attention found by Kelly et al. suggests that substantial individual differences in the anatomy of the early visual system may conceal attention effects when optimal presentation locations for eliciting the C1 are not chosen. Subsequent studies reporting an attention effect upon the C1 (e.g., Herde et al., 2022) now generally employ some degree of between-participant flexibility in choosing visual presentation sites. However, choosing optimal stimulus locations

based on individual C1 responses also cannot fully explain conflicting accounts of attention effects on the C1: Multiple replication attempts using this approach (Alilović et al., 2019; Baumgartner et al., 2018) also failed to show a difference between attended and unattended C1 waveforms.

A recent systematic review and meta-analysis (Qin et al., 2022) of three types of attentional manipulation (spatial attention, attentional load, and other attentional mechanisms) on the C1 reports a small to moderate effect (Cohen's *d* between 0.21 and 0.33). Findings first reported by Fox and colleagues and in the meta-analysis by Qin et al. (2022) support the view that attention exerts a graded effect throughout the visual hierarchy (Carrasco, 2011; Maunsell & Treue, 2006; Schneider & Kastner, 2009), including on the initial feedforward visual signal. Several explanations have been tendered to explain the discrepant findings regarding the impact of attention on the C1. A review of the literature (Slotnick, 2018) concluded that attention effects on the C1 are most pronounced under five conditions: when distractor stimuli are present, when perceptual or attentional load is high (see Lavie & Tsal, 1994) when cues are exogenous (involuntary), when the C1 is measured from parietal-occipital midline electrodes, and when stimuli are presented in the upper visual field. Of these, only the last two factors (parietal-occipital midline electrodes and upper field stimuli) unambiguously describe the paradigm of Clark and Hillyard (1996), though the sudden on/off visual stimulus presentation scheme could also have attracted exogenous attention. It has also been suggested (Foxe & Simpson, 2002) that there may be several sub-components of the traditional C1 waveform originating from multiple brain sources, and only the first 10-15 ms of the C1 reflects strictly feedforward, genico-striatal activity.

Because the present objective was to reproduce the specific experimental paradigm

employed in Clark and Hillyard (1996), previously suggested methods for best eliciting condition differences in the C1 waveform are not implemented. The above discussion including alternate C1 paradigms provides background for the ongoing debate as to whether directed spatial attention modulates this earliest index of visual processing detectable via scalp-recorded EEG (see discussions in Pitts & Hillyard, 2018; Slotnick, 2018). An unusual aspect of the debated effect of spatial attention upon the C1 is that most published claims rest upon the finding of a statistical comparison favoring the null. Instead of falling victim to the "file drawer effect", these null results have accumulated until they have come to affect current views in the field (Baumgartner et al., 2018). Under traditional null hypothesis statistical testing (NHST) procedures, a lack of evidence for an effect (i.e. a non-significant result) does not provide evidence that there is no effect (e.g., Aczel et al., 2018; Altman & Bland, 1995; Dienes, 2014; Makin & Orban de Xivry, 2019). In fact, Aczel and colleagues (2018) show, using Bayesian analysis, that non-significant NHST results typically fail to provide strong support in favor of the null hypothesis. On the other side of the debate, Di Russo (2020) points out that several claims of C1 attention effects rely on 'marginally significant' NHST results, which are difficult to interpret and often fail to replicate (Amrhein et al., 2019; Cumming, 2013; McGiffin et al., 2021). Dichotomizing outcomes based on NHST results is no longer a generally recommended practice (see Amrhein et al., 2019; McShane et al., 2019; Wasserstein & Lazar, 2016). The present report will replicate the original statistical (NHST) approach but will also employ Bayesian approaches to quantify the degree of support for the absence or presence of an attention effect on the C1.

In contrast to the C1 literature, there is currently little debate that unilaterally directed spatial attention amplifies both the P1 and N1 components of the visual evoked potential (e.g., Clark & Hillyard, 1996; Gomez Gonzalez et al., 1994; Hillyard et al., 1998; Luck et al., 1990;

reviewed in Mangun, 1995). Distinguishing between the effects of attention on the P1 and the N1, Luck and colleagues (1990) contended that P1 enhancement may index general spatial selective attention, whereas N1 enhancement reflects attentional orienting toward task-relevant stimuli. For instance, a discrimination task may sometimes be necessary in order to observe an N1 attention effect (e.g., Vogel & Luck, 2000), while the amplitude of the P1 increases for both task-relevant and task-irrelevant stimuli presented at attended locations (Heinze et al., 1990; Hillyard & Anllo-Vento, 1998). In addition to Clark and Hillyard (1996), numerous dipole modeling (reveiwed in Luck et al., 2000 and in Rauss et al., 2011) and combined ERP/fMRI studies (Mangun et al., 1997; Martinez et al., 1999; Martinez et al., 2001) indicate that the main neural generators of the P1 reside in extrastriate visual cortex. The N1 is a superposition of several distinct brain regions producing temporally overlapping negative voltages (Luck, 2014), preventing a general statement as to the single neural origin of this component. The present registered report aims to replicate previously reported attention effects on these three successive components.

The present work does not perform cortical dipole source modeling or any other source localization procedure. Focusing on the effects of attention at the sensor-level was done for several reasons. First, Clark and Hillyard (1996) obtained individual subject MRI scans (from 6 of the 17 total participants) onto which dipolar source estimates were projected, while MRI scanning was not conducted in the present effort. There is also little debate that the C1, P1, and N1 components can, in certain circumstances, be well represented by dipole source models originating in striate (C1) or extrastriate (P1, N1) visual cortex, respectively. Dipole source modeling, however, has limited spatial resolution accuracy (~ 1 cm; reviewed in Slotnick, 2004) which is insufficient to unambiguously distinguish between striate and extrastriate visual regions

(Slotnick, 2004). Dipole source estimates are also affected by the number of sensors (Slotnick, 2004) and low-pass data filtering (Cohen, 2014) that will necessarily differ slightly between the original study and the present replication effort.

Roughly separating the main conclusions presented in Clark and Hillyard (1996) into spatial (dipole modeling) and temporal (ERP) components, the present Registered Report represents an attempt to replicate only the latter. This replication effort will enable a quantitative evaluation, within the context of the original experimental paradigm, of the hypothesis that spatial attention does not modulate the C1 component of the visual evoked potential but does affect subsequent P1 and N1.

Method

This manuscript follows the recommended open science practices for psychophysiological research as outlined by Garrett-Ruffin et al. (2021). All study materials will be stored in a project repository on the Open Science Framework (https://osf.io/eq8ax/). The project repository will include code for stimulus presentation and data processing, and electrode configuration files that correspond to each replication site. The raw EEG data will be made publicly available in an appropriate repository (https://gin.g-node.org/EEGManyLabs/EEGManyLabs_Replication_ClarkHillyard1996_Raw).

Participants

The original study had a final sample size of 17 subjects. *A priori* power analysis on the basis of the estimated effect size (eta squared = .668) of the P1 amplitude difference between attended and non-attended presentations of the standard-sized checkerboard stimulus reported in Clark and Hillyard (1996) (specifically, the interaction effect of presentation side and attended side in 2 x 2 ANOVA) indicated that only 12 subjects would be needed to achieve 90% power. The #EEGManyLabs project (Pavlov et al., 2021) has adopted conservative sample size targets, based upon findings (OPEN SCIENCE COLLABORATION, 2015; Schäfer & Schwarz, 2019) that effect sizes derived from low-powered studies are likely to be inflated. Furthermore, one of the claims under investigation—attention effects upon the C1 amplitude —are based on null results in the original study. If an alternative hypothesis, namely that attention produces a graded effect throughout the visual hierarchy (Carrasco, 2011; Maunsell & Treue, 2006), predicts a correspondingly graded effect on the C1 and P1 (respectively), then studies powered to detect statistical differences in the P1 are likely to miss effects in the C1. Bearing these considerations

in mind and following the #EEGManyLabs project sample size guidelines of 90% power to detect 50% of the original effect size (i.e., eta squared = 0.334) at a 2% significance level for a one-sided test, 30 subjects (after data exclusions) will be collected from each of the 5 participating replication sites. The total number of participants included across all sites will be 150 and all activities under this replication were approved by local ethics committees at each site. With this total number of subjects, we will be able to detect effect sizes as small as eta squared = 0.1, or d = 0.308 in a one-sided t-test, which is comparable to the estimates of C1 effect size reported in the meta-analysis (Qin et al., 2022). At each location, the following information will be recorded: participant age, gender and biological sex assigned at birth, self-reported handedness, and need for corrected vision. At the Florida site, Race and Ethnicity will be recorded. Participants will be allowed to wear corrective lenses and glasses.

Stimuli

Visual stimuli were created in MATLAB (MathWorks) with the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2022), see Table 1 for all presentation software and accompanying equipment used in each replicating lab.

Visual stimuli are high contrast (white and black, Michelson contrast = 100%, maximum luminance approximately 90 cd/m^2) circular checkerboard patterns (see figure 1) presented against a black background. Checkerboard stimuli that deviate from the standard size serves as targets when shown in the attended location (see below). The circular checkerboard patterns will appear in quasi-random order at one of two positions (left or right) in the upper visual field, centered at 11.5° of visual angle above and 7.5° lateral to a central fixation dot, hence in the near periphery. Left and right visual field locations will be continuously indicated by four small white

dots (0.19° visual angle each) placed in a square pattern, the outline of which will subtend 2.4° of visual angle each. The presentation order will be random (MATLAB random number seed initialized at 123 prior to the first trial) with respect to which half of the screen stimuli would appear on. This is done to facilitate validation of stimulus conditions across laboratories, each having different EEG event marker setups (hard- and software). Presentation order is constrained such that target stimuli will be shown on only 10% of trials in each visual field location within each presentation block, target stimuli never appear consecutively, and a target will never be the first or last stimulus within any block. Standard checkerboard patterns, with a diameter subtending 2.3° of visual angle, will be shown on 80% of trials within each block. Target stimuli will begin at 65% of the diameter of standard stimuli and adjust adaptively between blocks, increasing or decreasing diameter in 5% or 10% increments depending upon identification performance. Stimuli will be presented individually for a duration as close to 50 ms as possible, as implementable by the monitor used in each participating laboratory (see refresh rates in Table 1, resulting in durations between 48.6 and 53.3 ms). Intervals between successive stimulus presentations (stimulus onset asynchrony, SOA) will vary randomly between 150 and 450 ms.

Procedure

Prior to beginning the experiment, participants will be led through detailed task instructions and shown example stimuli until they demonstrate an accurate understanding of the task. Participants will complete 30 blocks (runs) each of attend-left and attend-right conditions (60 total blocks), presented in random order. Each block contains 80 stimulus presentations, taking an average of ~ 40 s. At the beginning of each block participants will be instructed, via

on-screen text, to direct their attention (without moving their eyes and as will be confirmed by eye-tracking or horizontal EOG) to either the right or left stimuli, and to respond as quickly and accurately as possible to smaller checkerboard targets only at that location. Responses will be entered by pressing the spacebar on a standard size Qwerty keyboard. The responding hand will alternate between blocks. Responses will be classified as hits if they occurred between 200-1000 msec following target onset in the attended visual field. False alarms are responses that occur between 200-1000 msec following a standard (on-target) stimulus. Each between-block instruction screen will serve as a self-timed break period. Participants will be advised, using messages presented on-screen, when they have completed 25%, 50%, and 75% of the total trials in the experiment.

The difficulty of the discrimination task adjusts for each subject between blocks by varying the radius of the target stimulus. The target within-block accuracy is 80%. Target checkerboard patterns are initially 65% of the radius of the standards, and decrease (making discrimination easier) or increase (more difficult discrimination) by either 5% or 10% based upon accuracy in the previously completed block. Specifically, if performance is lower than 74% in a given block, the target will be made smaller by 10%, and if performance is better than 86%, the target will be made larger by 10%. All response times, stimulus adjustments, and accuracy data will be logged into dedicated logfiles. Accuracy will be calculated as the hit rate. False alarms will also be calculated as responses following non-targets within 1000 ms. Pilot testing performance indicates that the target 80% accuracy reported in Clark and Hillyard (1996) is a high standard that few participants in this replication effort are likely to achieve. Pilot test accuracy at the Florida site, after removing blocks with 0% accuracy (to eliminate blocks in which the instructions were missed, or other mental lapses occurred) was 68.9% (SD=7%) across

13 naïve test participants (see pilot data), similar to the empirically observed accuracy in Clark and Hillyard (1996) which was 73.9%. Across all pilot participants, there was no evidence of improvement or learning across blocks, and thus no initial training or block will be conducted.

Recording

Multi-channel EEG will be recorded using high-density EEG systems with sensor arrays ranging from 64 to 128 sensors, depending on the replication site. Therefore, strict EEG cap placement procedures will be implemented to improve the consistency of sensor locations across replication sites. Prior to recording, a midline measurement from inion to nasion and a lateral measurement from the left to right preauricular points will be used to center the cap vertex (sensor Cz) exactly at the midpoint between the midline and lateral position landmarks (see Farrens et al., 2020 for a detailed protocol). Conducting midline and lateral measurements will minimize the deviations in parietal and occipital midline sensor locations across replication sites. Furthermore, electrodes placed 1-2 cm laterally from the outer canthi of each eye will be used to record the horizontal electrooculogram (HEOG; Croft & Barry, 2000; Farrens et al., 2020). Recording parameters are reported in Table 1. Efforts will be made to standardize and remap event marker codes to facilitate harmonization across sites. The original protocol and analysis methods from Clark and Hillyard (1996) will be followed to the extent possible (see Table 2). In a deviation from the original study, several of the labs participating in this replication will monitor visual fixation with eye-tracking devices. In addition to eye-movement artifacts contaminating the EEG signal, fixation differences can cause spurious condition differences in the EEG (Dimigen & Ehinger, 2021). Importantly, hemifield effects as well as the presence of the C1 component itself require adherence to fixation. Even slight deviations from fixation, as

detected by eye-tracking, were shown to alter the amplitude of the C1 (Wolf et al., 2022). To maximize usefulness of the eye tracker data, initial calibration of eye position will be repeated halfway through the experiment. Data quality of time-varying gaze position will be monitored by examining the change in coordinates during the pre-stimulus baseline (200 ms before stimulus onset). At the trial level, gaze position changes in x or y coordinates that exceed 3 standard deviations of the respective values computed across all trials for that subject will be flagged for insufficient data quality. Similarly, trials with missing data will also be flagged for poor data quality. Therefore, only trials that survive gaze position data quality checks will be used to reject EEG data. For trials with sufficient data quality, trials in which there is evidence that foveation on central fixation was not kept (defined as a deviation by > 3 degrees of visual angle during the baseline and stimulus presentation time, in laboratories with eye trackers) will be excluded from the analyses.

In laboratories with no eye tracker, and in trials with insufficient gaze position data quality, the calibrated HEOG (Croft et al., 2005; Croft & Barry, 2000) will be used to identify and exclude trials with the same approximate deviation. Approximate deviations in fixation will be individually calibrated prior to beginning the experiment. In the calibration, participants will move their eyes left and right to foveate on lateral targets that are 3 degrees of visual angle away from central fixation, 10 times each, while HEOG is recorded. The purpose of calibrating the HEOG will be to obtain HEOG voltage values for each individual participant that can be used as a threshold for determining fixation adherence. This is intended to mirror the threshold used for the gaze position data in labs with eye tracker capabilities.

To explore the potential impact of slight deviations in foveation on central fixation on the C1, P1, and N1, the amplitude and topography of the components will be examined as a function

of eye position in a linear regression framework. This regression will be performed for each participant, each time point, and each channel separately. Following Wolf et al. (2022) we will regress the horizontal eye gaze position at stimulus onset, obtained for each trial, onto the corresponding trials' voltage data. Standardized betas will be obtained at the level of participants, time points, and channels, for each condition separately. These betas will then be tested against zero in a second-level analysis using permutation-controlled mass univariate t-tests. Any findings that are significant at the permutation-controlled level of $p<.05$ will be reported in the manuscript and will be followed up by recomputing the analyses discussed below, with amplitudes that are corrected by regressing out eye position. Both sets of analyses will then be reported in the manuscript. Furthermore, stimulus aligned traces of HEOG offset and horizontal eye gaze will be presented to visualize the time course, direction, and magnitude of slight deviations in foveation on central fixation relative to stimulus presentation location.

Table 1. EEG recording set up for each replicating lab

Participating University, Location	Amplifier System	EEG System, Number of Sensors	Sampling Rate (Hz)	Online Filter	Screen Type, Size, Refresh Rate	Stimulus Presentation	Recording Environment, Viewing Distance	Recording of Additional Data + Apparatus
University of Florida, USA	Electrical Geodesics (EGI System)	Geodesic Sensor Net (EGI System), 128 sensors	1000	LP filter: Elliptical filter 3-dB point at 200 Hz	Cambridge Research System Display++, 120 Hz	Psychophysics Toolbox version 3.0.18 (MATLAB)	Unlit Faraday chamber, 120 cm from display monitor and 60 cm from eye tracker lens	Gaze and pupil diameter, EyeLink 1000plus (SR Research) eye tracker
Stockholm University, Sweden	Active Two BioSemi	Electro-Cap International, 64 sensors	512	LP filter: 102.4 Hz	24-inch BenQ XL2430T monitor, 144 Hz	Psychophysics Toolbox version 3.0.18 (MATLAB)		
University of Münster, Germany	Active Two BioSemi	BioSemi, 64	512	LP filter: 102.4 Hz	ViewpixxEEG monitor, 100Hz	Psychophysics Toolbox version 3.0.18 (MATLAB)	Soundproof room with dim lights, 85 cm away from the computer screen (chinrest)	Gaze and pupil diameter, EyeLink 1000 (SR Research) eye tracker
Ghent University, Belgium	Active Two BioSemi	Electro-Cap International, 64 sensors	512	LP filter: 102.4 Hz	19’ inch CRT monitor (1600 x 1200 resolution at 75 Hz)	Psychophysics Toolbox version 3.0.18 (MATLAB)	Electrically shielded and soundproof room with dim lights; 60 cm away from the computer screen (chinrest)	Gaze and pupil diameter, EyeLink 1000 (SR Research) eye tracker
Liverpool John Moores University, UK	Active Two BioSemi	BioSemi, 64 sensors	512	LP filter: 102.4 Hz	27-inch LG UltraGear 27GS95QE-B OLED monitor, 144 Hz	Psychophysics Toolbox version 3.0.20 (MATLAB)	Electrically shielded room with dim lights, 60 cm away from the computer screen (no chinrest)	

Offline Preprocessing with common pipelines

The preprocessing pipelines to be used are shown in Table 2. In a first pipeline that approaches the original method used by Clark and Hillyard as closely as feasible (Table 2, left), the following steps are implemented. Off-line the data will be down-sampled to 500 Hz and re-referenced to the right mastoid or the sensor closest to the right mastoid to conform to the original procedure (Clark & Hillyard, 1996, p. 398). The C1, in particular, can be substantially modulated by the settings of the high-pass filter applied to the data (Acunzo et al., 2012). The commonly recommended frequency cutoff of 0.1 Hz (Luck, 2014; Widmann et al., 2015) for ERP studies is adopted here.

Short inter-stimulus intervals (ISIs) can distort ERP averages due to temporal overlap from longer-latency brain responses to preceding stimuli, and this distortion is not entirely eliminated by randomly jittering the ISIs (Woldorff, 1993). The original ADJAR algorithm, implemented in MATLAB code will be used (Woldorff, 1993, Method 1) to correct for these overlapping responses. To enable ADJAR, continuous EEG data will be segmented into 900 ms epochs (-450 ms before stimulus onset to 450 ms after stimulus onset). Trials with eye movements will not be retained but will be rejected because deviation from fixation alters the topography of the C1, P1, and N1 and may eliminate the C1 altogether if participants foveate on the stimulus. Finally, averaged ERPs will be filtered at 1.2 Hz high-pass and 46 Hz low-pass as in the original publication by Clark and Hillyard. If more than 50% of trials are excluded in a given participant, then the participant's data are not included in the analysis.

An updated pipeline will also be used, incorporating contemporary approaches for EEG preprocessing, using what are considered more appropriate filter settings: Off-line filtering of the

EEG data will be use native matlab butterworth filter design function butter.m and the zero-phase filter filtfilt.m. High-pass (3dB point 0.1 Hz) and low-pass (3dB point 30 Hz) Butterworth filters will be applied separately and successively (Widmann et al., 2015). A state-of-the art, reproducible artifact rejection method will be used for detecting and rejecting bad epochs (Junghofer et al., 2000), with standard settings, run without user intervention. Bad channels will be detected based on statistical properties across the data sets and interpolated using spherical spline interpolation in the updated pipeline (Junghofer et al., 2000; Keil et al., 2014). No more than 8% of the available channels will be interpolated. If more than 8% of channels require interpolation throughout the experiment in a given participant, that participant's data will not be included. If more than 50% of trials are excluded in a given participant, then the participant's data will also not be included in the analysis.

No filtering of the averaged event-related potentials will be performed. The average reference will be used, and conversion to that reference will be completed at the stage of averaging artifact-free segments, after artifact handling. Target ERPs will be used in the ADJAR approach but will then be discarded throughout and only VEP responses to standard stimuli are evaluated in hypothesis testing (see below).

If results obtained with the two pipelines differ in terms of the conclusions drawn, both sets of results will be reported and discussed extensively in the manuscript, but the results of the updated pipeline will be prioritized in the final assessment of the replication, because the elements of the updated pipeline (filter settings, updated artifact rejection) are known to yield more robust estimates of event-related brain activity (Keil et al., 2014).

Table 2. Offline processing pipeline comparison between original and updated pipeline

Offline Processing	**Original Pipeline**	**Updated Pipeline**
Sampling Rate	Downsample to 500 Hz	Downsample to 500 Hz
Channel interpolation	Spherical splines	Spherical splines
Offline Filter	Butterworth HP: 0.1 Hz FIR filter[2] (3rd order) LP: 45 Hz FIR filter (13th order)	Butterworth HP: 0.1 Hz FIR filter[2] (3rd order) LP: 30 Hz FIR filter (11th order)
EEG Segmentation	Stimulus-locked -450 to 450 ms	Stimulus-locked -450 to 450 ms
Baseline Correction	-100 – 0 ms	-100 – 0 ms
EOG/Eye tracker Artifact Correction	Remove epochs in which deviations in eye position, and blinks occurred (EOG> 50 μV)	Remove epochs with horizontal eye movements > 3 degrees of visual angle
EEG Artifact Rejection	Remove amplifier blocking artifacts and epochs with voltage fluctuations > 100 μV. Remove epochs preceded by a target (800 ms) or followed by a target (500 ms) to mitigate target related activity	Remove outlying trials (including trials with blinks) and interpolate any bad channels within remaining trials using SCADS (Junghöfer et al. 1997). Remove epochs preceded by a target (800 ms) or followed by a target (500 ms) to mitigate target related activity
Overlap Removal	ADJAR algorithm (Woldorff, 1993)	ADJAR algorithm (Woldorff, 1993)
Averaged VEP Filtering[2]	HP: 1.2 Hz Single pole causal filter LP: 46 Hz FIR	none[2]
Reference	Right mastoid or closest analog to the right mastoid[1]	Average reference[3]
ERP Quantification[4]	Mean amplitude averaged over VEPs to left and right stimuli	Mean amplitude averaged over VEPs to left and right stimuli

[1]Each lab will be using EEG systems that do not directly conform to the modified 10-20 electrode system montage used in the original recording procedure (see Clark et al., 1994 for exact sensor locations).
[2]Early VEPs can be substantially modulated by the settings of the high-pass filter applied to the data (Acunzo, MacKenzie, & van Rossum, 2012), therefore the updated pipeline will also consider unfiltered averaged VEPs.
[3]This references will facilitate comparing topographies across laboratories, using all available sensors and reducing effects of the original recording reference (Junghöfer et al., 1999).
[4]Latency ranges and sensor locations chosen from Clark & Hillyard (1996) can be found in Table 3. Mean amplitudes will be measured from sensors closest to the sensor locations in Table 3.

Preliminary Data

Pilot data were collected at the Florida location and at two other sites to examine feasibility and data quality. ERP data from 4 naïve participants recorded at the Florida site are presented in Figure 2. Waveforms are shown at the sensor locations corresponding to those chosen by Clark and Hillyard (1996; see Table 3), showing attended standards in the attend-left conditions. Across four observers, the data demonstrate that component latencies and topographies are consistent with those reported by Clark and Hillyard (1996). Specifically, plot data show that the rising ramp and peak of the C1 component is captured by a 60 to 90 ms window, and the early and late P1 captured by an 85 to 140 ms window, while showing the expected contralateral topography, paralleling Clark and Hillyard (1996), Figure 2. An additional 13 participants performed the task without EEG recordings taken, and their target detection accuracy (hit rate) is shown in Figure 3 together with the accuracy data from the 4 ERP participants discussed above. Plot data illustrate that the task, while challenging, is feasible for the undergraduate student participants that were invited to the pilot recordings shown.

Table 3. Sensor locations and latency ranges chosen following Table 1 in Clark and Hillyard (1996)

Component	**Latency (ms)[1]**	**Sensor location[2,3]**
C1	60-90	(IPz/IPz)
P1 (contralateral)	105-125	(IN3/IN4)
P1 (ipsilateral)	120-140	(IN4/IN3)
N1	170-190	(IN3/IN4)

[1]Latency window used to calculate mean amplitudes.
[2]Amplitude measurements will be taken from sensors closest to these sites, using the Cartesian distance based on the original extended 10-20 configuration and the electrode configurations used in each laboratory. The first channel listed will be used for VEP measurement in right visual field stimulus conditions, and the second channel will be used for VEP measurement in left visual field stimulus conditions.
[3]Mean amplitudes will be averaged over VEPs to left and right stimuli.

Statistical Analysis:

The analytical plan of this replication attempt includes two main thrusts:

1. A direct replication of the statistical approach used in the original study, based on null hypothesis testing and repeated measures analyses of variance (ANOVA).
2. We will examine the robustness of the findings across the laboratories using Hierarchical linear Bayesian models.

Direct replication approach (1)

Amplitudes of VEP components will be calculated after subtracting the average amplitude in the 100 ms time window preceding stimulus onset (-100 ms to 0 ms) within subjects for each stimulus presentation. Latency ranges and sensor locations will be chosen following Table 1 in Clark and Hillyard (1996, p.390; see Table 3). Should substantial deviations from the documented ERP latencies be detected, the new latencies will be found as the latency range surrounding the grand mean peak for each component, collapsed across conditions, each with the same duration as the original time windows from Clark and Hillyard (1996), respectively. Statistical comparisons will then be run both with amplitudes based on the original and new time windows. Statistical comparisons will be performed via repeated-measures ANOVA in JASP (Wagenmakers et al., 2023), with side of presentation (left or right) and attended side (left or right) as crossed factors. Effect sizes (partial Eta Squared) and confidence intervals will be reported throughout. Only VEP responses to standard stimuli are to be compared.

Replication success was defined in the #EEGManyLabs protocol (Pavlov et al., 2021). For each component (C1, N1, P1) separately, we will, first, compute effect sizes (Pearson's r, Fisher's z-transformed, estimated from the partial eta squared for the interaction of presentation side and attended side effect) for each individual lab and then combine all datasets in a random-effects meta-analysis (with labs as a random effect) using the REML estimator for random-effects variance. Employing a random-effects meta-analysis will address and help in estimating

the effect of heterogeneity in EEG devices and samples between labs. For N1 and P1, the replication will be considered successful if a statistically significant meta-analytic estimate ($p < .02$) across replicating labs is observed and if the effect is in the expected direction (larger N1 and P1 in the attended condition). For C1, the replication will be considered successful if the effect is not significantly different from zero ($p \geq 0.02$). We will report distribution of the weighted effect sizes, their 95% confidence intervals, heterogeneity ($\tau 2$). The metafor package (Viechtbauer, 2010) for R will be used for the meta-analysis.

Bayesian Hierarchical Linear Models (2)

Regardless of whether the results from the direct replication approach reach statistical significance, we will use Bayesian Hierarchical Models (BHM) to estimate the strength of the evidence both for and against the hypothesis that spatial selective attention modulates the amplitude of the components of interest (C1, P1, N1). Specifically, we will model ERP amplitude, for each component separately and measured as described above, using a 2-level BHM, with the first level unit being Participant, and the second level unit being Laboratory. Slopes and intercepts are free to vary between laboratories, and effects of attention (attended versus unattended) are estimated as parameters of interest for each visual field (left, right). Flat uninformative priors will be used for estimates of Laboratory and Participant means and standard deviations, which are modeled by normal distributions and half-normal distributions respectively. Hamiltonian MCMC sampling will be used for parameter estimation, implemented in STAN programming language through the CmdStan interface in the R environment (https://mc-stan.org/docs/2_35/cmdstan-guide/index.html). Posterior distributions of attention effects for each component (C1, P1, N1) and visual field (Left, Right) will be generated with

1000 burn-in samples and 5000 subsequent samples using 8 sampling chains. Trace plots and Rsquare will be used to examine the extent to which that the posteriors were correctly estimated and that the sampling converged. If convergence is not achieved, priors will be adjusted accordingly. Posterior distributions will be tested for robustness to changes in the choice of priors by adjusting the SD of the prior distributions and rerunning analyses, seeking converging evidence. Deviations from convergence will be noted in the manuscript. Posterior results will be reported with their median value as well as the inner 95% of samples, which will be referred to as the credibility interval (CI). Credibility intervals in the predicted direction and not including zero will be taken as evidence of support for the attentional modulation of a given component and visual field.

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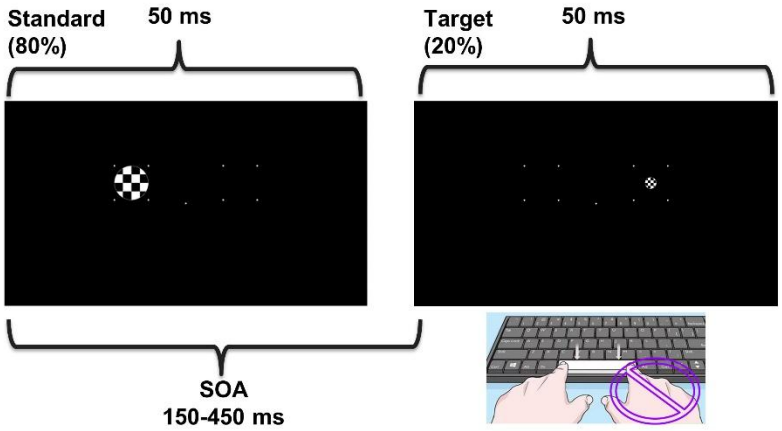

Figure 1. Experimental diagram. An example sequence of the rapid serial visual presentation (RSVP) paradigm is shown. Response hand alternated between blocks. Spacebar responses were made only to targets appearing in the attended visual field, as directed by an instruction screen prior to each block. Size of target stimuli started out at 65% of the size of the standard checkerboards. Size of targets was adjusted between blocks based on target identification performance.

Figure 2. Pilot data from 4 naïve observers. Each observer's mean ERP across standard trials in the attend-left condition is shown as a separate line. Data as shown were analyzed with the updated pipeline. Differences to the original pipeline were minimal. Data were recorded at the Florida site. Topographies are averaged across the four observers, illustrating the voltage topography, which parallels the latencies and topographies seen in Clark and Hillyard (1996). Note that in the present manuscript, positive is plotted up, negative down. The opposite plotting (negative up) was used in Clark and Hillyard (1996).

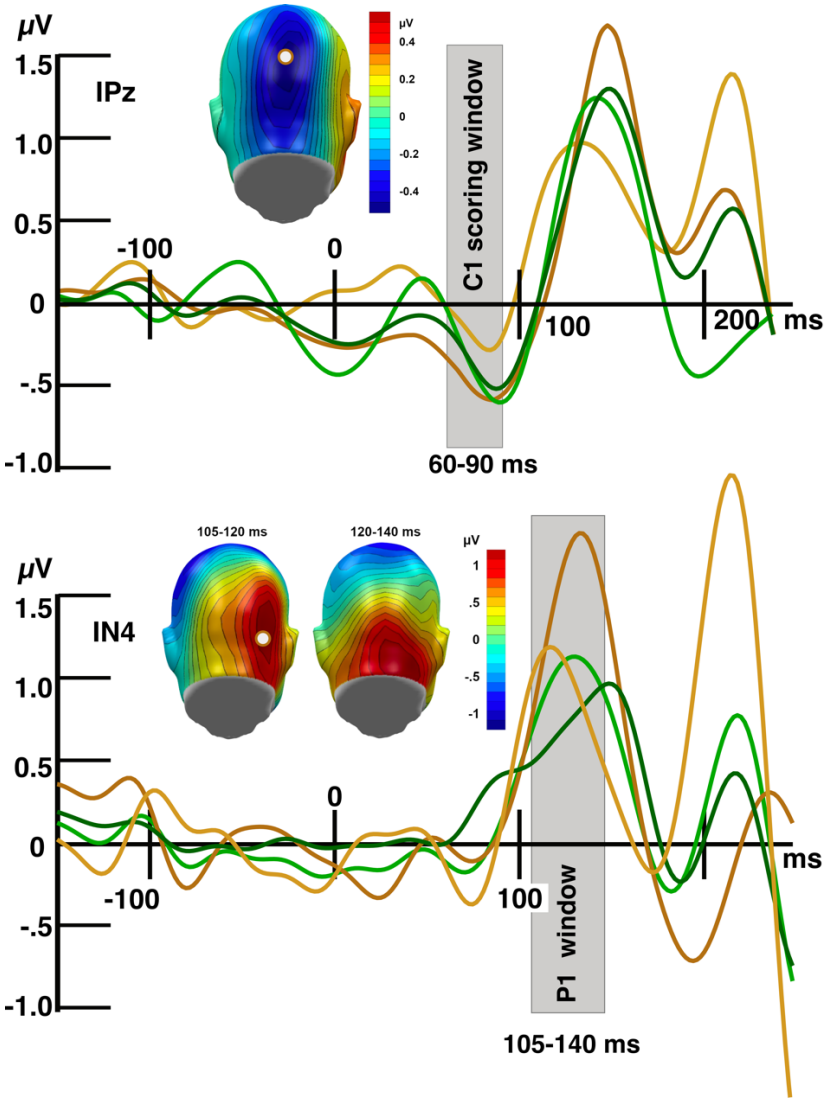

Figure 3. Accuracy pilot data from 17 naïve observers. Each observer's mean accuracy is shown as a bar. Although several participants showed low accuracy, the majority was in the targeted range near 80%.