

Transient Distraction and Attentional Control during a Sustained Selective Attention Task

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Abstract

■ Distracting stimuli in the environment can pull our attention away from our goal-directed tasks. fMRI studies have implicated regions in right frontal cortex as being particularly important for processing distractors [e.g., de Fockert, J. W., & Theeuwes, J. Role of frontal cortex in attentional capture by singleton distractors. *Brain and Cognition*, 80, 367–373, 2012; Demeter, E., Hernandez-Garcia, L., Sarter, M., & Lustig, C. Challenges to attention: A continuous arterial spin labeling (ASL) study of the effects of distraction on sustained attention. *Neuroimage*, 54, 1518–1529, 2011]. Less is known, however, about the timing and sequence of how right frontal or other brain regions respond selectively to distractors and how distractors impinge upon the cascade of processes related to detecting and processing behaviorally relevant target stimuli. Here we used EEG and ERPs to investigate the neural consequences of a perceptually salient but task-irrelevant distractor

on the detection of rare target stimuli embedded in a rapid, serial visual presentation (RSVP) stream. We found that distractors that occur during the presentation of a target interfere behaviorally with detection of those targets, reflected by reduced detection rates, and that these missed targets show a reduced amplitude of the long-latency, detection-related P3 component. We also found that distractors elicited a right-lateralized frontal negativity beginning at 100 msec, whose amplitude negatively correlated across participants with their distraction-related behavioral impairment. Finally, we also quantified the instantaneous amplitude of the steady-state visual evoked potentials elicited by the RSVP stream and found that the occurrence of a distractor resulted in a transient amplitude decrement of the steady-state visual evoked potential, presumably reflecting the pull of attention away from the RSVP stream when distracting stimuli occur in the environment. ■

INTRODUCTION

While focusing on a goal-directed task, such as writing, our attention may be pulled away from the task at hand by a salient, unexpected stimulus in the environment, such as a sound on your computer signifying the arrival of a new e-mail message. Although at times the ability of environmental stimuli to pull our attention away from other tasks can be behaviorally useful, like when a fire alarm signals that you should stop writing and evacuate the building, at other times these stimuli are simply behaviorally irrelevant distractors impeding our ability to focus on a behaviorally relevant task.

In the context of visual attention, the features or qualities that can make a stimulus distracting include being perceptually salient (e.g., Burnham, Neely, Naginsky, & Thomas, 2010; Lamy, Tsal, & Egeth, 2003; Rauschenberger, 2003; Theeuwes, 1991a, 1991b), having an abrupt onset or offset (e.g., Grubb, White, Heeger, & Carrasco, 2015; Folk, Remington, & Wu, 2009; Jonides & Irwin, 1981; Yantis & Jonides, 1984), having proximity to a target stimulus in time or space (e.g., Leonard, Balestreri, & Luck, 2015; Seibold & Rolke, 2014; Theeuwes, 1995), or sharing features with a target stimulus (e.g., Lamy, Leber, & Egeth,

2004; Folk, Remington, & Johnston, 1992). The boundary conditions of what properties make a stimulus behaviorally distracting and whether top-down, goal-oriented attention can override potential distractors have been intensely studied and debated, particularly in the additional-singleton literature (e.g., Theeuwes, 1992). For example, the presence of an irrelevant but perceptually salient distractor item has been shown to impair behavioral performance in identifying a relevant target stimulus. Similarly, in the contingent attentional capture literature (e.g., Folk, Leber, & Egeth, 2002; Folk et al., 1992), the capture of attention depends on whether the distractor stimulus shares a property that is part of participants' task-relevant top-down "set." The perceptual load of a task has also been shown to affect distractor processing (e.g., Elliott & Giesbrecht, 2015; Lavie, 2005).

In contrast to the relatively more extensive behavioral literature, the literature is much more sparse regarding the neural effects of distraction. In a recent ERP study of visual search, Gaspar and McDonald (2014) found that successfully ignoring salient distractors was associated with the "PD" component, an ERP marker of attentional suppression. In the context of attentional blink paradigms, where processing of a first target in a rapid, serial visual presentation (RSVP) stream impairs detection of a second target depending on the timing between target stimuli,

distractor stimuli in the stream that share features with the target have been shown to also reduce detection of the second target and to reduce the amplitude of the P3 ERP component associated with the processing of the second target (Pincham & Szucs, 2014). In the neuroimaging literature, fMRI studies have implicated regions in right frontal cortex as being especially important when distraction challenges attentional control, (e.g., Marini, Demeter, Roberts, Chelazzi, & Woldorff, 2016; de Fockert & Theeuwes, 2012; Demeter, Hernandez-Garcia, Sarter, & Lustig, 2011), but the precise role of this region and whether it activates directly in response to distractor stimuli themselves or more broadly to contexts where attentional control is needed is still unclear.

Here, we used EEG recordings of brain activity to explore the neural effects of distraction on selective attention using a novel twist on a classic RSVP paradigm, which we have termed the distractor RSVP (dRSVP) task. In our task, participants centrally fixated while covertly attending to an RSVP stream just above fixation consisting of frequent nontarget letters and rare target numbers. Meanwhile, a task-irrelevant but perceptually salient checkerboard distractor stimulus was infrequently presented with unpredictable timing just below fixation. We were first interested in investigating how the timing of the distractor occurrence would affect the behavioral detection of target stimuli in the RSVP stream and what the neural consequences of distraction would be for the ERPs generated by target stimuli. Second, we were also interested in investigating the ERPs generated by the distractor stimuli themselves. On the basis of the neuroimaging literature (e.g., Demeter et al., 2011), we predicted that distractors would evoke a right frontal neural response. Finally, we also sought to analyze the effect of distraction on the envelope of the instantaneous amplitude (IA) of the steady-state visual evoked potential (SSVEP) generated by extrastriate visual cortical neurons in response to the flickering RSVP stream. An SSVEP is an oscillatory brain response at the same fundamental frequency as the driving stimulus, and previous work has demonstrated that SSVEP amplitudes increase when attention is directed towards the driving stimulus and decrease when attention is directed away from the driving stimulus (e.g., Andersen, Müller, & Martinovic, 2012; Müller et al., 1998, 2006). We predicted that distractors would temporarily pull participants' attention away from the RSVP stream, which would be evidenced by a transient decrement in the SSVEP amplitude time-locked to the distractor occurrence.

METHODS

Participants

Participants were 20 young adults (eight women, age = 21–36 years, mean = 26.2 years) with normal or corrected-to-normal vision who did not report any neurological disorders or conditions that could affect attention or memory. All

participants provided informed consent before beginning the study, and participants were financially compensated at a rate of \$15/hr. Participant recruitment, consent, and experimental procedures were in accordance with protocols approved by Duke University's institutional review board.

dRSVP Task

For the dRSVP task (Figure 1), participants maintained fixation on a central point while covertly attending to an RSVP stream presented just above fixation. The RSVP stream consisted of letters (Nontargets) and infrequent numbers (Targets; 8% of stimuli) presented at a rate of 116-msec duration per stimulus (8.6 Hz). All of the RSVP stimuli were black, and the background screen was gray. Participants were instructed to buttonpress whenever they detected a number Target. Meanwhile, a brief checkerboard Distractor stimulus occasionally and unpredictably flashed just below fixation. The black and white pattern of the checkerboard alternated with each presentation. The Distractor was presented with a random distribution (minimum time between distractors = 500 msec, maximum time = 1050 msec, flat distribution) for a duration of 33 msec. The Distractor stimulus onset could occur 0, 16, 33, 50, 66, 83, or 100 msec (i.e., at any screen refresh with a 60-Hz refresh rate) after the onset of a stimulus in the RSVP stream. This temporal jittering of the Distractor relative to the RSVP stimuli ensured that the SSVEP signal evoked by the RSVP task stream would be averaged out in the ERPs time-lock averaged to the Distractor onset (cf. Crist, Wu, Karp, & Woldorff, 2008). Finally, all stimuli were kept along the vertical midline to facilitate extraction of predicted right frontal components associated with distractor processing (see Introduction). Participants were familiarized with the task and all procedures and then completed 15 three-minute runs of the dRSVP task while EEG data were recorded. Three additional

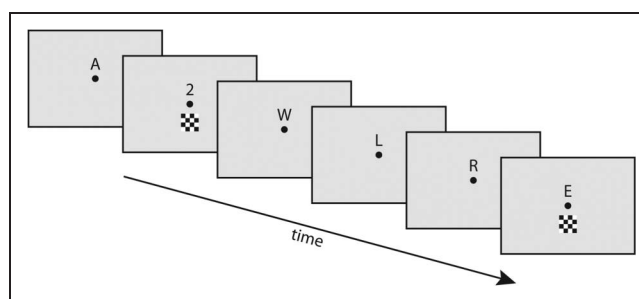


Figure 1. dRSVP task. Participants fixated on a central dot while covertly attending to an upper-field RSVP stream consisting of letters and infrequent numbers. Each stimulus in the RSVP stream was presented for 116 msec (8.6 Hz) with no gap between stimuli, and participants were instructed to buttonpress every time a number appeared. Meanwhile, below fixation, an irrelevant checkerboard distractor (33-msec duration) flashed every 500–1050 msec.

3-min runs of the RSVP task without any distractors were also collected.

EEG Recording

EEG was recorded with a 63-channel active electrode system (Brain Vision actiCHamp, Brain Products, Gilching Süd, Germany) using a customized, extended coverage, elastic electrode cap (Woldorff et al., 2002; EASYCAP, Herrsching, Germany). These caps were designed to have an extended coverage of the head from just above the eyebrows to below theinion posteriorly and to have electrodes that are equally spaced across the cap. An electrode was placed below the left eye to monitor vertical eye movements, and two electrodes somewhat lateral to the left and right outer canthi were used for monitoring lateral eye movements. The scalp sites of our equidistant electrode custom cap are reported in terms of the closest location in the standard 10–10 system if within a couple of millimeters. For any electrodes further than a couple of millimeters from the related 10-10 electrode, the electrode is denoted with a subscript of “a,” “p,” “i,” or “s” for slightly “anterior,” “posterior,” “inferior,” or “superior”, respectively. Relevant electrodes are also specifically identified on schematic head figures in the Results section. The EEG (and EOG) data were recorded with a bandpass from DC to 138 Hz, sampled at 500 Hz per channel, and referenced to the right mastoid. Data were subsequently re-referenced offline to the algebraic average of the two mastoids.

Behavioral Analyses

To examine the behavioral effects of distraction on target detection, Targets were categorized on the basis of when a Distractor onset occurred relative to the onset of the RSVP Target stimuli to create the following six bins: Bin 1: –348 to –232 msec before the onset of a Target, Bin 2: –232 to –116 msec, Bin 3: –116 to 0 msec, Bin 4: 0–116 msec following the onset of a Target, Bin 5: 116–232 msec following, or Bin 6: 232–348 msec following. The width of each of these bins (116 msec) corresponds to the duration of one stimulus in the RSVP stream. Accuracy and RTs for detecting Targets were analyzed using repeated-measures ANOVAs with the factor of Bin (six levels). The Greenhouse–Geisser sphericity correction was applied as needed. Corrected F and p values are reported, but degrees of freedom are rounded to integer values for easier reading. Significant ANOVA main effects were further queried using post hoc t tests where appropriate.

ERP Analyses

ERP analyses were conducted using EEGLab and ERPLab software (Lopez-Calderon & Luck, 2014; Delorme & Makeig, 2004). Offline, data were bandpass filtered from 0.01 to 30 Hz using an infinite impulse response

Butterworth noncausal filter with a 12-decibel per octave roll-off. Epochs with eye movements, blinks, or muscle movements were excluded from analyses using ERPLab’s automated artifact detection algorithms, with settings optimized for each participant. The number of epochs rejected did not systematically differ between conditions. For each participant, Detected Targets, Missed Targets, and Nontargets were categorized by when a Distractor stimulus occurred using the same timings as the six bins created for the behavioral analyses. ERPs were created by time-lock averaging the epoched EEG data to the onset of Detected Targets, Missed Targets, and Nontargets within each of the six bins, as well as to the onset of the Distractor stimuli. The selectively averaged ERPs were baseline corrected by subtracting the mean amplitude of the baseline period (–200 to 0 msec) from the ERP for each time-locked stimulus. Specific contrasts and subtractions to isolate functional activations are described in detail in the appropriate sections of the Results. ANOVAs on the mean amplitudes over specified time ranges were conducted to test statistical differences between responses to different stimulus conditions as described in further detail below. The Greenhouse–Geisser sphericity correction was applied as needed.

SSVEP IA Analyses

We hypothesized that distraction would temporarily pull participants’ attention away from the RSVP task stream and that this temporary reduction in attention would be reflected by a decrease in the envelope of the IA of the SSVEP generated by the steady-state RSVP stream. To test this hypothesis, we created epochs (–600 to 1000 msec) time-locked to Nontargets without a Distractor, to Nontargets with a Distractor 0–116 msec following the Nontarget onset, and to the Distractor stimuli. Epochs containing Target stimuli were excluded from this analysis. For the Nontarget-without-Distractor epochs, data from the three RSVP task runs without distraction were used. For the Nontarget-without-Distractor and Nontarget-with-Distractor conditions, the envelope of the IA of the SSVEP signal generated by the RSVP task was estimated by convolving the epoched EEG data with a complex Morlet wavelet (see also Gladwin, Lindsen, & de Jong, 2006). The frequency mean of the wavelet was set to 8.6 Hz, the driving frequency of the RSVP stream, and the standard deviation in the frequency domain was set to 2 Hz (equivalent to a standard deviation of 80 msec in the time domain). To control for the physical presence of the Distractor stimulus in the Nontarget-with-Distractor condition, we wanted to subtract out the Distractor’s contribution in the 8.6-Hz frequency band within the relevant time range from the Nontarget-with-Distractor IA values. To extract the content in the 8.6-Hz frequency band from the Distractor response, we convolved the complex Morlet wavelet (frequency mean = 8.6 Hz, standard deviation = 2 Hz) with the time-lock averaged ERP response to the

Distractor stimuli. As the Distractor could have occurred at seven possible onset times relative to the onset of a Nontarget stimulus (0, 16, 33, 50, 66, 83, or 100 msec later), we then convolved the resulting data with a 7-point delta function corresponding to these possible onset times. Finally, we subtracted these Distractor IA values from the IA values for the Nontarget-with-Distractor condition, giving us corrected IA values for this condition. We predicted the corrected Nontarget-with-Distractor condition would show a temporary reduction in the IA values, reflecting the brief pull of attention away from the task stream. In contrast, we predicted the Nontarget-without-Distractor condition would show a consistent IA over time.

RESULTS

Behavior

Distractors that Occur during the Presentation of a Target Interfere with Detection of Those Targets

The behavioral results for the dRSVP task are shown in Figure 2. Figure 2A shows the proportion of Targets detected as a function of when a Distractor onset occurred relative to the onset of a Target stimulus. Overall, the proportion of Targets detected was 0.69 ± 0.03 . There was a significant main effect of Bin on the proportion of Targets detected ($F(5, 95) = 5.73, p = .001$). Pairwise comparisons of the Bins revealed that Targets were most likely to be missed when a Distractor onset occurred 0–116 msec following the Target onset (Bin 4; paired t tests between Bin 4 and all other bins, all $ps < .04$). Accuracy was the highest for Bins 2 (Distractor –232 to –116 msec before Target) and 3 (Distractor –116 to 0 msec before Target; paired t tests between Bins 2 and 3 and Bins 1, 4, and 6, all $ps < .04$). There was no effect of Distractor onset time on the RTs for successfully Detected Targets (Figure 2B; main effect of Bin, $F(5, 95) = 0.68, p = .64$).

Electrophysiology

Distraction Reduces P3 of Missed Targets

We next examined the effect of distraction on the neural processes related to target detection by analyzing the EEG data to create ERPs time-lock averaged to the onset of the Target and Nontarget stimuli. For these analyses, Targets were coded on the basis of whether they were successfully detected or missed behaviorally. Detected Target, Missed Target, and Nontarget ERPs are shown in Figure 3A. Detected Target, Missed Target, and Nontarget stimuli were categorized into the six time bins outlined in the Methods section, based on when a Distractor onset occurred relative to the Target or Nontarget onset. To isolate the functional activity associated with target detection more specifically, we subtracted the Nontarget ERPs from the Detected and Missed Target ERPs, respec-

tively, to create difference waves. These difference waves also controlled for the physical presence of the Distractor stimuli as both Targets and Nontargets were identically binned according to when Distractors occurred. We first examined these difference waves for Detected and Missed Targets, irrespective of when Distractors occurred, and then examined whether these ERPs varied as a function of when a Distractor stimulus onset occurred. As the targets were occurring relatively rarely (8% of total stimuli) and were task relevant, we predicted that they would elicit

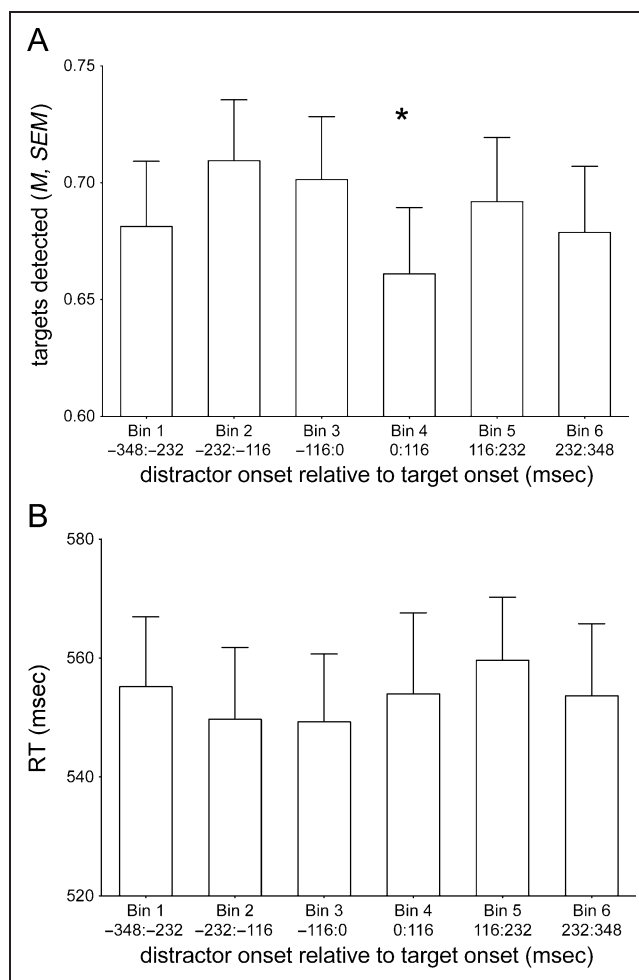


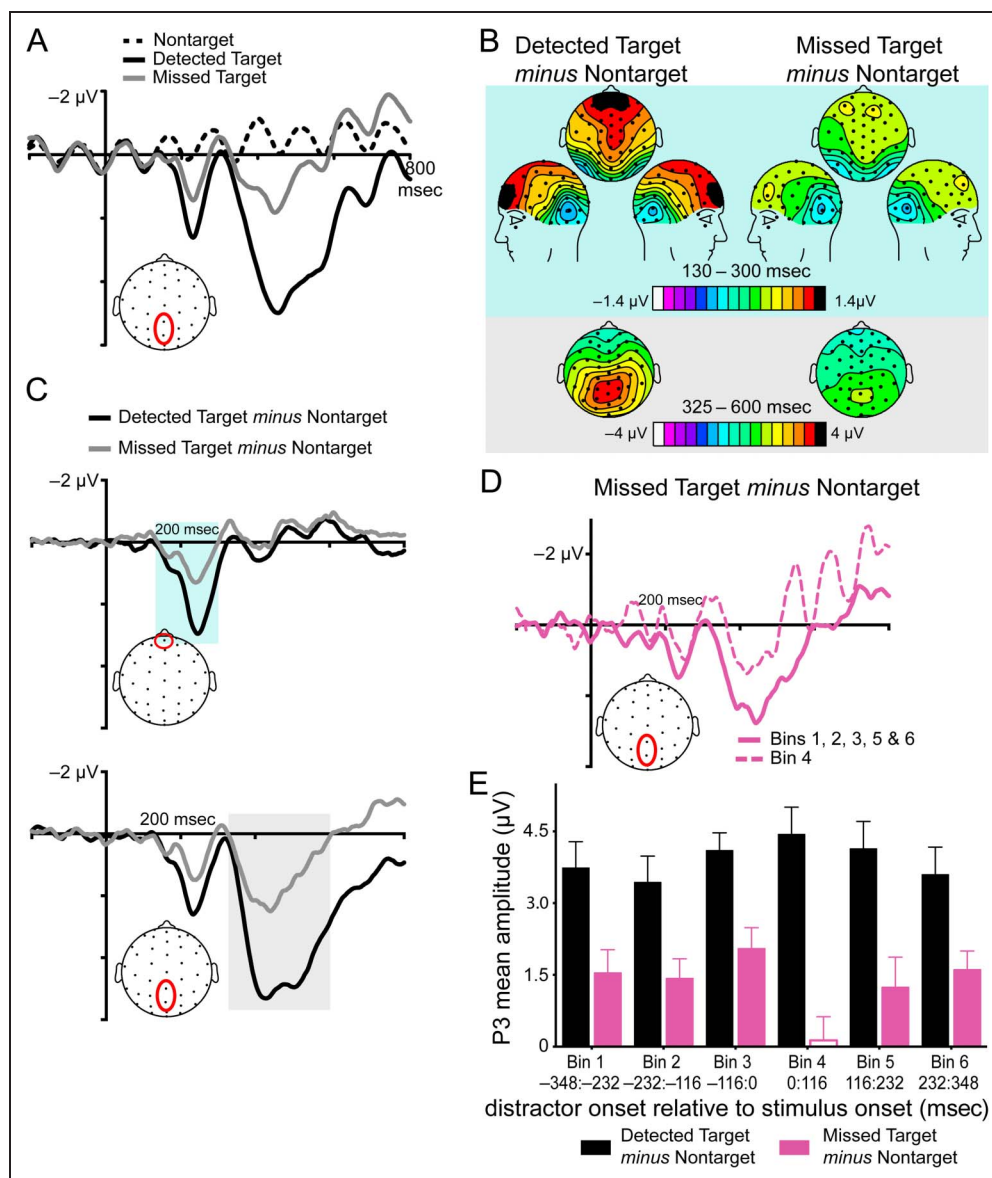
Figure 2. Target detection is impaired when a distractor is presented 0–116 msec following the target onset. (A) Bars represent the mean proportion of Targets detected as a function of when a Distractor onset occurred relative to the onset of a target stimulus. Error bars represent the between-subject standard error around the mean. When a Distractor onset occurred 0–116 msec following the onset of a target stimulus, the detection of those Targets was significantly impaired compared with the proportion of Targets detected when Distractors were presented in other time windows (paired t tests between Bin 4 and every other bin, all $ps < .04$). (B) Bars represent the mean RT for correctly detecting Targets as a function of when a Distractor onset occurred relative to the onset of a Target stimulus. Error bars represent the between-subject standard error around the mean. There were no significant effects of the Distractor occurrence timing on the RTs.

Figure 3. Effects of detection and distraction on target-related neural activity. (A) Detected Target, Missed Target, and Nontarget ERP waves from a centroparietal ROI. To isolate target-related activity, as well as to subtract off the ongoing SSVEP activity overlapping on these event-related responses, we also calculated the difference waves between Detected Targets and Nontargets and Missed Targets and Nontargets. Targets that were behaviorally detected generated larger ERP responses than Targets that were ultimately missed. These effects were most evident in an early frontocentral positivity (130–300 msec, blue shading) and in a later large centroparietal positivity (P3 component, 325–600 msec, gray shading). (B) Topographic scalp maps of the mean amplitudes extracted in these two latency windows for both Detected Targets minus Nontargets and Missed Targets minus Nontargets. (C) Detected Target minus Nontarget and Missed Target minus Nontarget difference waves from channel AFz and from a centroparietal ROI. For the P3 component, in addition to showing an effect of Detection, there was also an interaction between Detection and Bin, indicating the size of this component was also modulated by the timing of the distractor stimulus (see text for statistical details). Further analyses revealed that

the P3 amplitude for Detected Targets minus Nontargets was unaffected by the timing of Distractors, but the P3 for Missed Targets minus Nontargets were smaller when Distractors onset occurred 0–116 msec following Target onset (Bin 4). (D) ERP difference waves for Missed Targets minus Nontargets specifically for Bin 4 (dashed line) and for the average across the other five bins (solid line). (E) Mean amplitude from 325 to 600 msec for Detected Targets minus Nontargets (black bars) and Missed Targets minus Nontargets (pink bars). These data were categorized into the six bins based on when a Distractor onset occurred relative to the onset of a Target. Error bars represent the between-subject standard error around the mean.

a P3 wave as is often seen in traditional oddball paradigms or in other RSVP tasks with rare targets (see review by Polich, 2007). We also hypothesized that Missed Targets in our task would generate a smaller P3 than Detected Targets. On the basis of our behavioral data, we further hypothesized that Distractors that onset 0–116 msec following a Target would impair the neural processing of that Target, as reflected by a reduced amplitude P3, compared with when the Distractor onset occurred in the other relative time windows.

Figure 3 illustrates the data from these analyses. Detected Targets minus Nontargets showed an early frontocentral positivity starting around 130 msec and peaking



around 245 msec. This positivity was the largest over anterior channels. This effect was smaller and slightly less anterior in the Missed Targets minus Nontarget waves (Figure 3B and C). This early positivity may be related to the previously reported prefrontal positivity or “pP” component (Perri, Berchicci, Lucci, Spinelli, & Di Russo, 2015a, 2015b; Perri, Berchicci, Spinelli, & Di Russo, 2014), also called the Go-P2 in the literature (Gajewski & Falkenstein, 2013). This component is thought to reflect stimulus–response mapping processes before response execution. As predicted, Detected Targets minus Nontargets also generated a large P3 component, as evidenced by a large positivity strongest over centroparietal channels

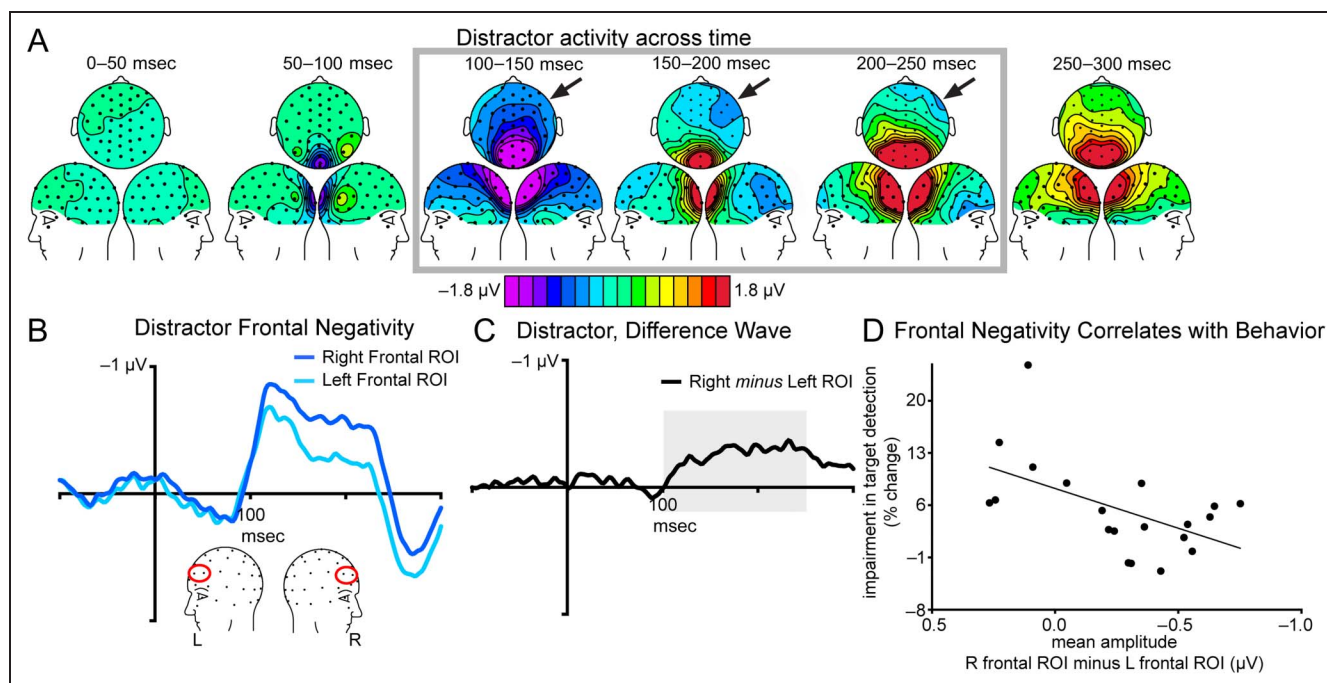


Figure 4. Distractors evoke a right-lateralized frontal negativity. (A) Topographic scalp maps of the mean amplitude over time of the ERP response time-lock averaged to the onset of the Distractor. A right-lateralized negativity between 100 and 250 msec was observed (gray outline box, activity indicated by black arrows). (B) To explore this negativity, ERP responses time-lock averaged to the Distractor onset were extracted from ROIs created over left and right frontal channels. The right frontal ROI response (dark blue trace) was significantly more negative than the left frontal ROI response (light blue trace; paired t test on the mean amplitudes of the ERP response between 100 and 250 msec, $t(19) = 4.412$, $p < .01$). (C) The right frontal ROI minus the left frontal ROI difference wave. The mean amplitude of this difference wave between 100 and 250 msec (shaded in gray) was extracted and used in a correlational analysis with behavior. (D) The size of the mean amplitude difference between the right and left frontal ROIs negatively correlated with the amount of impairment individuals showed when the Distractor was presented 0–116 msec following the onset of a Target (see text for analysis details). That is, individuals who showed a bigger difference between the right and left frontal ROIs also showed less behavioral impairment in target detection when Distractors were presented.

and beginning around 325 msec. This positivity was strongly attenuated in the Missed Targets minus Nontarget difference waves (Figure 3B and C).

To more specifically investigate the effects of distraction on target-related activity, the Detected Target minus Nontarget difference waveforms and, separately, the Missed Target minus Nontarget difference waveforms were binned into the six time windows based on Distractor onset times. For the early frontocentral positivity, mean amplitudes from 130 to 300 msec were extracted from an ROI created by averaging the data from the frontocentral channels FCz, Cz, C1a, and C2a. These mean amplitudes were subjected to a repeated-measures omnibus ANOVA with the factors of Detection (Detected, Missed) and Bin (six levels). For this frontocentral positivity, there was a main effect of Detection ($F(1, 95) = 29.75$, $p < .0001$), but no effect of Bin and no interaction between Detection and Bin. Thus, although this component was larger when the Target was ultimately behaviorally detected than when it was not, the timing of the Distractor stimuli did not differentially affect the component.

Identical analyses were conducted on the P3 component by extracting the mean amplitudes from 325 to 600 msec from an ROI over centroparietal sites where

this positivity was the strongest (channels Pz and CPz; see Figure 3A for a diagram). As before, these mean amplitudes were subjected to a repeated-measures omnibus ANOVA with the factors of Detection (Detected, Missed) and Bin (six levels). Significant effects were further queried with repeated-measures ANOVAs and paired t tests separately for the Detected Target minus Nontarget and Missed Target minus Nontarget data. The results of the omnibus ANOVA revealed a significant main effect of Detection, with the Detected Target minus Nontarget P3 mean amplitudes being larger than those observed for the Missed Target minus Nontarget condition ($F(1, 19) = 49.70$, $p < .01$). There was no main effect of Bin ($F(5, 95) = 0.99$, $p = .43$). The Detection \times Bin interaction was significant ($F(5, 95) = 3.95$, $p < .01$), indicating that the Distractors could have a differential effect on Detected and Missed Targets depending on when the Distractors occurred. To explore this interaction, we next conducted repeated-measures ANOVA with the factor of Bin (six levels) separately for the Detected Target minus Nontarget data and the Missed Target minus Nontarget data. There was no main effect of Bin on the P3 amplitude for the Detected Target minus Nontarget condition ($F(5, 95) = 1.84$, $p = .11$), suggesting that Targets that were successfully detected behaviorally were unaffected by

the timing of the Distractor. However, for the Missed Target minus Nontarget condition, the effect of Bin was significant ($F(5, 95) = 2.41, p = .04$; Figure 3D and E). For these data, the P3 amplitude for the Missed Target minus Nontarget condition was smallest for Bin 4, when the Distractor onset 0–116 msec following the onset of the Target and Nontarget stimuli (Figure 3D and E), paralleling the behavioral impairment results. Paired t tests between Bin 4 and the other bins revealed Bin 4 was significantly smaller than all other bins (all p s < .05), with the exception of Bin 5, the comparison with which did not reach significance ($p = .09$). There were no other significant differences on these components between bins.

Distraction Induces a Right-lateralized Frontal Negativity that Correlates with Reduced Behavioral Impairment

To investigate the neural activity associated with distractor processing, we created ERPs time-lock averaged to the onset of the Distractor stimuli (Figure 4). Figure 4A shows the topography of the mean amplitude of the ERP response to the Distractor over time. Notably, although our stimuli were all presented along the vertical midline, these data revealed a frontal negativity that appeared to be larger on the right side of the scalp than on the left (Figure 4A, outlined in gray and indicated by the black arrows). We explored this right-lateralized frontal negativity by creating ROIs over left and right frontal cortex (Channels F3a, F3i and F4a, F4i, respectively) and then extracting from both ROIs the ERP response time-lock averaged to the Distractor onset (Figure 4B). Figure 4C illustrates the right ROI minus the left ROI ERP difference wave. The mean amplitude of this difference wave was calculated in 50-msec intervals between 0 and 1000 msec post-Distractor onset to determine where it was significantly greater than zero. This analysis revealed that the difference wave was significantly greater than zero between 100 and 250 msec (all p s < .04). It did not significantly differ from zero between 250 and 300 msec ($t(19) = 2.05, p = .054$). There were a few 50-msec intervals that again achieved significance after 300 msec, and then the difference wave was consistently no longer different from zero following 600 msec.

As noted in the Introduction, previous neuroimaging work has indicated regions in right frontal cortex to be particularly important for distractor processing and for the implementation of top-down attentional mechanism in response to distractor challenges (e.g., Demeter et al., 2011). Given this, we next wanted to further explore the functional characteristics of this right-lateralized negativity induced by the distractor, in particular whether it correlated with participants' behavioral performance on the RSVP task. As participants' showed a selective impairment in the proportion of Targets detected when Distractors were presented 0–116 msec following Target onset

(Bin 4), we calculated the percent change between participants' Bin 4 accuracy and their average accuracy over the remaining five bins to index the behavioral effect of distraction. We then correlated these behavioral data with the mean amplitude of the difference between the right and left frontal ROI ERP responses between 100 and 250 msec (Figure 4D). These data demonstrated that the right-lateralized negativity in the ERP response to Distractors was correlated with a reduction in behavioral impairment with distraction ($r = -0.53, p = .02$)—that is, the more right-lateralized the frontal response to the Distractor, the less the corresponding behavioral impairment.

Distraction Pulls Attention Away from the RSVP Stream, Modulating the SSVEP IA

Figure 5 depicts topographic plots of the IA of the SSVEP over time (–150 to 750 msec relative to Nontarget onset) for the Nontarget-without-Distractor (Figure 5A) and the corrected Nontarget-with-Distractor conditions (Figure 5B). The largest IA values were observed over posterior channels, as would be expected for these visual SSVEPs. Averaging together the Nontarget-without-Distractor and corrected Nontarget-with-Distractor condition data revealed that the largest IA values of the averaged data occurred over channel Pz. To statistically analyze the effect of distraction on the IA values for both the Nontarget-without-Distractor and the corrected Nontarget-with-Distractor conditions, the IA from channel Pz was averaged within six 150-msec intervals (relative to the time-locked Nontarget onset: –150 to 0 msec, 0–150 msec, 150–300 msec, 300–450 msec, 450–600 msec, and 600–750 msec). These values were then subjected to a 2×6 repeated-measures ANOVA with the factors of Distraction and Time. This analysis revealed a significant Distraction \times Time interaction ($F(5, 95) = 14.79, p < .01$), as well as significant main effects of both Distraction ($F(1, 19) = 21.97, p < .01$) and Time ($F(5, 95) = 24.84, p < .01$). To further probe the Distraction \times Time interaction, separate 1×6 ANOVAs were conducted within each of the two Nontarget conditions (see Table 1A for means). In the absence of distraction, the IA of the envelope of the SSVEP evoked by the 8.6-Hz driving frequency of the RSVP task stream remained nearly constant over the course of the epoch (no main effect of Time, $F(5, 95) = 2.38, p = .11$). In contrast, when a Distractor occurred 0–116 msec following the onset of a Nontarget (with the sensory effect of the Distractor removed), there was a significant main effect of Time ($F(5, 95) = 21.97, p < .01$). More specifically, the IA values decreased starting in the 0- to 150-msec interval, reaching their lowest point in the 150- to 300-msec interval and then returned to their predistractor values by the final 600- to 750-msec interval. This reduction of the RSVP SSVEP following the Distractor occurrence suggests reduced attentional allocation to the RSVP stream.

As is evident from the topographic plots showing the difference between the Nontarget-without-Distractor

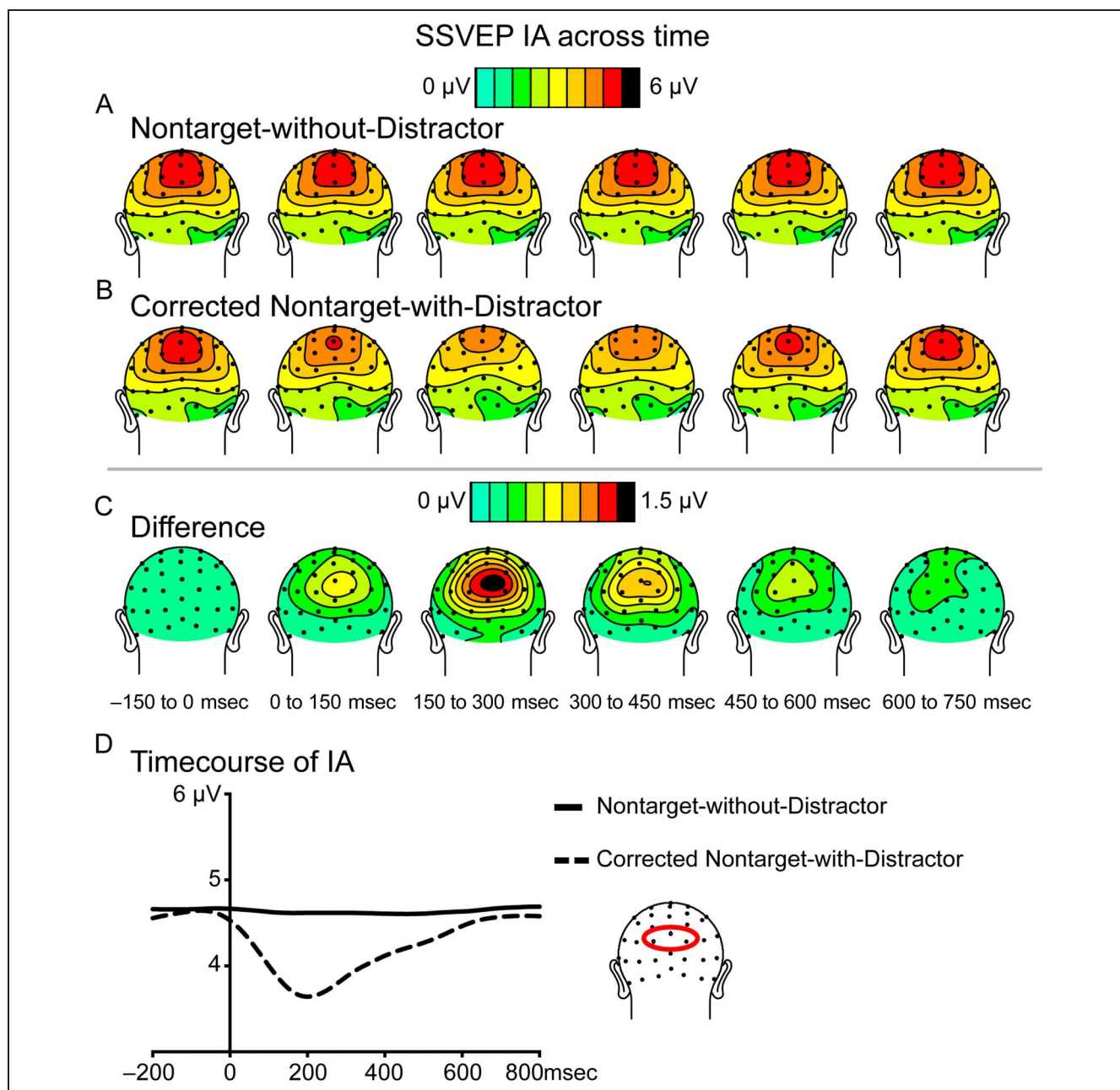


Figure 5. The IA of the SSVEP over time. Topographic plots represent data from epochs time-locked (A) to the onset of Nontarget stimuli in the absence of Distractors, (B) to the onset of Nontargets when Distractors occurred (Distractor onsets 0–116 msec relative to Nontarget onset, corrected for sensory activity of the Distractor itself; see Methods for additional details), and (C) the difference between these two conditions. Note that no pre-Distractor baseline correction was performed on these data. As is clear in the maps, the IAs were the largest over posterior channels. For the Nontarget-without-Distractor condition, data from three RSVP runs without distraction were used. (D) The extracted time course of the IA. Data are the IA values over time averaged within a posterior ROI (illustrated). Without Distractors, the IA of the envelope of the SSVEP generated by the RSVP task stream remained nearly constant over time. In contrast, Distractor presentation resulted in a modulation of the SSVEP envelope (lower amplitude), implicating reduced attentional allocation to the RSVP stream.

and corrected Nontarget-with-Distractor conditions (Figure 5C), the greatest difference between these conditions was observed over channels POz, O1, and O2. For completeness, we created an ROI based on these channels as well. The time course of the IA from this ROI is plotted in Figure 5D. Subjecting this ROI to the same Distraction \times Time repeated-measures ANOVA as run for channel Pz revealed a significant Distraction \times Time

interaction ($F(5, 95) = 21.64, p < .01$; see Table 1B for means), as well as significant main effects of Distraction ($F(1, 19) = 22.61, p < .01$) and Time ($F(5, 95) = 20.29, p < .01$). Again, the Nontarget-without-Distractor condition showed a nearly constant SSVEP IA over time (no main effect of Time, $F(5, 95) = 1.02, p = .41$), whereas the corrected Nontarget-with-Distractor condition showed a significant effect of Time ($F(5, 95) = 23.08, p < .01$),

Table 1. IAs, Averaged within 150-msec Time Intervals

Condition	Time Interval Relative to Nontarget Onset (msec)					
	-150 to 0	0-150	150-300	300-450	450-600	600-750
<i>A. Means for Channel Pz</i>						
Nontarget without Distractor	5.73 (0.60)	5.71 (0.60)	5.75 (0.62)	5.80 (0.63)	5.81 (0.64)	5.84 (0.64)
Corrected Nontarget with Distractor	5.69 (0.61)	5.26 (0.63)	4.78 (0.59)	5.13 (0.55)	5.44 (0.58)	5.67 (0.59)
<i>B. Means for Channels POz, O1, and O2</i>						
Nontarget without Distractor	4.66 (0.55)	4.64 (0.54)	4.62 (0.54)	4.61 (0.54)	4.62 (0.55)	4.66 (0.55)
Corrected Nontarget with Distractor	4.62 (0.55)	4.15 (0.56)	3.71 (0.51)	4.06 (0.46)	4.32 (0.47)	4.55 (0.50)

Data are means (*SE*) of the IA in microvolts for the Nontarget-without-Distractor and corrected Nontarget-with-Distractor conditions. Significant differences between conditions are indicated in **boldface** (paired *t* tests, all *p*s < .05).

with the IA values reaching their lowest point in the 150- to 300-msec interval.

Size of IA Decrement Correlates with Behavioral Impairment

We next explored whether the distraction-related decrease in the SSVEP IA correlated with behavioral performance, using the same index of behavioral impairment with distraction as used in the previous correlational analysis. We hypothesized that more distracted individuals would have a larger decrease in IA with the occurrence of a Distractor and that this would correlate with a larger behavioral impairment. To test this hypothesis, we created a posterior ROI based on channels showing the greatest difference between the Nontarget-without-Distractor and corrected Nontarget-with-Distractor conditions (channels POz, O1, and O2; see Figure 6 for illustration). Within this ROI, the average IA from 0 to 600 msec was calculated for each condition. We found that the difference between the Nontarget-without-Distractor condition and the corrected Nontarget-with-Distractor condition correlated with participants' behavioral impairment with distraction ($r = 0.49$, $p = .03$), such that the larger the decrease in the SSVEP observed with distraction, the greater the behavioral impairment in target detection.

DISCUSSION

In the present work, we presented a brief but salient, task-irrelevant distractor in a temporally unpredictable fashion while participants performed an RSVP task. We predicted that the distractor would temporarily pull participants' attention away from the RSVP task, resulting in missed RSVP targets and a reduction in the IA of the SSVEP generated by the RSVP stream. We also predicted the distractor stimulus itself would elicit activity over right frontal cortex, in line with the existing attentional control neuroimaging literature. We found that distract-

tors that occurred during the presentation of RSVP targets interfered with the detection of those targets, resulting in more missed targets when distractors onset 0–116 msec following the onset of a target than when distractors occurred either before or farther away in time from the presentation of a target. In line with these behavioral data, the P3 elicited by missed targets when distractors occurred in this time window were smaller in amplitude compared with missed targets with distractors that occurred in other time windows. Furthermore, time-lock averaging to the distractor stimulus itself revealed a frontal negativity that was larger over right frontal channels than over left frontal ones from 100 to 250 msec following

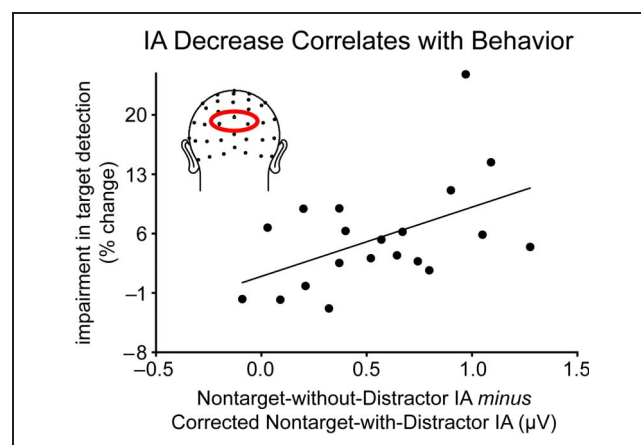


Figure 6. Decrease in IA correlates with behavioral impairment. The decrease in IA of the RSVP SSVEP due to distraction correlated positively across participants with participants' impairment in target detection. For this analysis, the average IA was extracted from a posterior ROI (illustrated) from epochs time-locked to the onset of Nontargets with and without Distractors (latency used 0–600 msec). These values were then entered into a correlational analysis with the same accuracy measures used for Figure 4D (i.e., degree of impairment in the critical 0–116 msec bin window for Distractor occurrence). The results indicate that the larger the decrease seen in the IA with distraction, the greater the behavioral impairment also observed.

the distractor. The difference in amplitude between the right and left frontal negativity (i.e., its right-sidedness) correlated with participants' behavioral impairment such that the more right-lateralized this component was, the less behavioral impairment a participant showed for targets in the distraction-susceptible window of 0–116 msec following target onset. Finally, we also found that the SSVEP generated by the task stream decreased in amplitude when distractors were presented. We were able to perform this analysis and extract this result on epochs containing nontarget stimuli only, where there was no direct behavioral index of distraction. However, we found that the size of the IA decrease with distractors positively correlated across participants with their distraction-related behavioral impairment, suggesting that the more distracted individuals were by the irrelevant flashing checkerboard, the more their attention was pulled away from the RSVP stream and the more RSVP targets they missed.

Although the brief distractors used here produced statistically significant impairments in target detection, the behavioral effects (change in targets detected) were nonetheless fairly small in magnitude. Notably, our distractor stimuli (checkerboards), which appeared in a different but nearby location relative to the task-relevant stimulus stream, did not share a target-defining feature with the targets in that stream. It has been theorized that distractors that share a target-defining feature capture attention because they correspond to the top-down “set” participants have established to facilitate target detection (contingent attentional capture; Folk et al., 1992, 2002). Accordingly, we might have been able to get larger behavioral effects of distraction if our distractors shared a distinct feature with our target stimuli (e.g., if RSVP targets were red items among gray nontargets, with distractors also being red). However, as one of our aims was to look at the neural response to the distractor stimuli themselves, we elected to make the distractor featurally different than the targets. Related to this discussion, other ERP studies of behavioral distraction have also found novel, infrequent distractors can significantly impair attentional performance (e.g., Berti & Schröger, 2001; Escera, Alho, Winkler, & Näätänen, 1998). In our study, it is possible that rarer distractors could have resulted in more behavioral distraction than our higher-frequency distractor stimuli. However, this would have also resulted in fewer trials per condition in our current design. Additionally, our RSVP stimuli were always presented above fixation and our distractors below fixation. Future work will be needed to explore whether and how changing the location of these stimuli affects behavior and task-related brain activity.

In our data, the distractor had the most influence on target detection when it occurred during the presentation of a target stimulus. Sato and Kawahara (2015) found similar behavioral effects using task-irrelevant face distractors, demonstrating that faces presented either simultaneously with targets or at a very short SOA relative to targets resulted in attentional capture, whereas the pre-

sentation of face distractors at longer SOAs relative to targets did not result in attentional capture. These authors argued that this pattern of results could be a consequence of people's ability to quickly and efficiently process naturalistic stimuli, resulting in a rapid attentional engagement with disengagement from the distractor stimuli. Our checkerboard distractor was not a naturalistic visual stimulus, but it was presented very briefly (33-msec duration), which could also trigger relatively rapid attentional shifting to the distractor and then quickly back to the relevant task stream. In contrast to the role of relative timing in the current data, the typical temporal pattern of capture effects by color singletons in the contingent attentional capture literature is quite different. For example, Folk et al. (2002) found peripheral color singletons presented approximately 200 msec before a uniquely colored central target in a stream of nontargets captured attention and resulted in impaired detection of those subsequent targets. Similarly, in the attentional blink literature (e.g., Raymond, Shapiro, & Arnell, 1992), the presentation of a target (T1) or a disruptor stimulus (typically also sharing some feature with targets) 150–500 msec before a second target (T2) disrupts detection of the T2. These different patterns in when distractor presentation have been observed to have the most behavioral impact suggests different mechanisms may underlie why or how these distractors operate to disrupt behavior. However, of note, Pincham and Szucs (2014) found task-set-colored distractors in an attentional blink paradigm reduced both accuracy for the T2 and the amplitude of the P3 component it elicited. As our data also found effects of distraction on target P3 amplitudes, this suggests that the downstream consequences of distraction on target processing may be similar across these different paradigms.

A particularly novel aspect of our findings is the right-lateralized frontal negativity from 100 to 250 msec that we observed in the ERPs time-locked to the distractors. Right frontal activity during attentional control tasks or in the presence of distraction has been demonstrated in fMRI studies (e.g., Marini et al., 2016; de Fockert & Theeuwes, 2012; Demeter et al., 2011; Leber, 2010; Serences et al., 2005), and the importance of this region in attentional control has been underscored in both human lesion (Japee, Holiday, Satyshur, Mukai, & Ungerleider, 2015) and animal lesion and neurochemical work (St Peters, Demeter, Lustig, Bruno, & Sarter, 2011; Passetti, Chudasama, & Robbins, 2002). Although ERP studies have also contributed to the large body of evidence that frontal cortex in general is important for attentional control (e.g., Shomstein, Kravitz, & Behrmann, 2012; Grent-'t-Jong & Woldorff, 2007), many of these studies have made use of lateralized stimuli and/or experimental designs that would hinder the isolation of right-lateralized neural responses to distraction (e.g., where distractors are temporally paired with targets or where activity due to stimuli in the ipsilateral visual field is subtracted from activity due to stimuli in the contralateral visual field). In our experiment, we presented our stimuli

along the vertical midline and temporally jittered the presentation of distractors relative to the onsets of the RSVP stimuli to facilitate extraction of hypothesized right-lateralized frontal components.

In Berti and Schröger (2001), infrequent distractor stimuli elicited ERP components related to early sensory processing, followed by P3a (~350 msec poststimulus) and reorienting negativity (RON; ~500 msec poststimulus) components. This pattern was interpreted as distractor stimuli activating brain regions associated with detecting novel stimuli (as reflected by the P3a activity) and then triggering a reorienting of attention away from the distractor (as reflected by the RON). In our experiment, distractor stimuli did not elicit a RON-like component but rather showed a relatively sustained right-lateralized frontal negativity beginning around 100 msec following distractor onset. We also found that the amplitude of this component negatively correlated with distraction-related behavioral impairments across participants (larger for participants with less distraction-related impairment), suggesting that enhancement of this neural process component is beneficial to attentional performance. It is possible that infrequent distractors may trigger reactive reorienting processes whereas frequent distractors may trigger more proactive, sustained control mechanisms (see Marini et al., 2016, for a discussion on proactive vs. reactive responses to distraction and Bledowski et al., 2004, for a discussion of the brain regions associated with processing visual distractors and targets). The present work helps better connect the ERP attention literature to the findings observed with other techniques, particularly fMRI, while also marshaling the high temporal resolution of ERPs to reveal the timing of the right frontal activity for distraction resistance and its selective elicitation by the distractor itself.

In addition to our target- and distractor-related ERP findings, we also investigated how distraction affected the envelope of the SSVEP elicited by the constantly flickering RSVP stream. Although the ERPs are transient brain responses to a particular event in time, the SSVEPs are a continuous brain response at the same frequency as the driving stimulus—in this case, the 8.6 Hz RSVP stream. SSVEP amplitudes are known to be enhanced by attention and reduced when an input is suppressed (see review by Andersen, Müller, & Hillyard, 2011), and other studies have used the “frequency-tagging” of stimuli to study the effects of spatial and feature-based attention, including the time course of visual cortical facilitation following attentional cues (Müller et al., 1998), the ability to concurrently direct the attentional spotlight to more than one spatially distinct location (Müller, Malinowski, Gruber, & Hillyard, 2003), and the enhancement and suppression of inputs based on feature selection (Andersen & Müller, 2010). Here, we found that distractor presentation resulted in a transient dip in the envelope of the SSVEP signal. This finding, combined with the positive correlation across participants between this amplitude decrease and the distractor-related behavioral impairments in target de-

tection, provides neural evidence that the distractors temporarily pulled attention away from the RSVP task stream, resulting in reduced cortical facilitation of the task-relevant input stream. Future work could examine how manipulating other characteristics of the distractor, such as its spatial distance from the task stream or whether it had any task-related features, influences the distractor’s effect on the SSVEP signal or how the presence of multiple distractors may influence the SSVEP signal.

In conclusion, we found that the presentation of a brief, task-irrelevant distractor pulled participants’ attention away from an on-going task stream. Distraction resulted in both a behavioral and neural impairment in target detection and processing, as well as reduced cortical responses of the ongoing task input stream. Distractors also elicited a temporally specific, right-lateralized frontal negativity that could be related to the right-lateralized attentional control and distractor-processing activations observed with fMRI. Future work will be necessary to determine what other types of distractors are capable of eliciting this right frontal ERP response and to confirm that this component is beneficial for attentional control. As many patient populations show reductions in their attentional control capabilities compared with healthy individuals, such as patients with schizophrenia (Demeter, Guthrie, Taylor, Sarter, & Lustig, 2013), attention deficit hyperactivity disorder (Friedman-Hill et al., 2010), or Alzheimer’s disease (Perry & Hodges, 1999), it would also be of substantial interest to investigate how this right frontal component presents in these populations.

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