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The Flickering Spotlight of Visual Attention: Characterizing Abnormal Object-Based Attention in Schizophrenia

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Abstract

Schizophrenia is associated with deficits in both object perception and visual attention. However, few studies in schizophrenia have investigated object-based attention, which is dissociable from other forms of visuospatial attention. Recent research in healthy populations has shown that the 'spotlight' of sustained visual attention flickers in a rhythmic, oscillatory fashion at specific frequencies in the 4–12Hz range. In healthy samples, this oscillatory signature has been used to investigate spatiotemporal dynamics of object-based attention, showing that the attentional spotlight spreads to uncued locations within cued objects, and also periodically alternates focus between cued and uncued objects. In this study, we adapted a performance-based visual object cueing task to investigate object-based attention in individuals with a schizophrenia diagnosis and healthy controls. In controls, spatiotemporal patterns of object-based attention closely resembled those reported in previous studies of healthy individuals. In the schizophrenia group, the oscillatory signature of attention also appeared in the location of the cue and on uncued objects, similar to the effects in controls. Indeed, the oscillatory signature of attention at the spatial location of the cue was stronger in the schizophrenia group than in controls. However, attention did not spread across the cued object in schizophrenia; rather, attention appeared to remain hyperfocused at the spatial location of the cue. These findings provide the first evidence that visual attention has oscillatory characteristics in schizophrenia, as in the general population. The results also show that the fundamental process of attentional spreading which underlies object-based attention is abnormal in schizophrenia.

1. Introduction

Schizophrenia is associated with specific deficits in perception and attention. These known deficits include impairments visual object perception (e.g., integrating discontinuous object contours, recognizing object identities during backward masking) (Butler et al., 2008; Green et al., 2011; Javitt, 2009; Silverstein, 2016; Silverstein and Keane, 2011). Attentional impairments in schizophrenia are also well-established, but almost all studies in this area

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A new paper by @EricReavisPhD, @DrJonWynn, & @MichaelFGreen3 shows that visual attention has oscillatory characteristics in schizophrenia, as in the general population. It also identifies a fundamental deficit of object-based attention in schizophrenia. [link to paper]

have focused on general vigilance (e.g., continuous performance tests), visuospatial attention (e.g., Posner cueing), or sometimes feature-based attention (e.g., visual search) (Braff, 1993; Cornblatt and Keilp, 1994; Fuller et al., 2006; Luck and Gold, 2008; Nuechterlein, 1977; Orzack and Kornetsky, 1966; Spencer et al., 2011). Thus, despite independent lines of evidence pointing separately toward aberrant object perception and abnormal attention in schizophrenia, object-based attention has hardly been investigated in psychosis.

Object-based attention is a specific type of visual attention that has been studied in healthy humans and other primates since the 1980s (Duncan, 1984; Egly et al., 1994). While object-based attention often operates in concert with spatial attention, experimental findings demonstrate that allocation of attention to visual objects is dissociable from allocation of attention to spatial locations (Carrasco, 2011). Several experimental paradigms have shown that visual attention tends to spread automatically across the surface of visual objects, beyond the immediate vicinity of spatially localized cues (Ernst et al., 2013; He and Nakayama, 1995; Houtkamp et al., 2003; Reppa et al., 2010; Roelfsema and Houtkamp, 2011; Wannig et al., 2011).

Recent studies in healthy samples have identified a striking spatiotemporal signature of sustained attention. Specifically, these studies have shown that the ‘spotlight’ of visual attention flickers rhythmically at a relatively low frequency, with oscillations in the 4–12 Hz range (for recent reviews, see Helfrich et al., 2018 and Kienitz et al., 2021). These attentional oscillations can be assessed using performance-based measures. In such experimental paradigms, a series of attentional cues and targets are presented at various tightly controlled latencies. Regular fluctuations in target detection ability for specific locations within the visual field typically occur at these specific 4–12Hz frequencies, which are linked to ongoing neural oscillations (Helfrich et al., 2018; Kienitz et al., 2021). To our knowledge, no study has yet tested whether such rhythmic fluctuations in visual attention occur in schizophrenia.

In the context of object-based attention, research in healthy populations shows that the unique signature of attentional flicker appears at uncued spatial locations within cued objects (Fiebelkorn et al., 2013). Thus, attentional flicker provides a useful way of assessing the spread of attention across objects. Healthy individuals also tend to show oscillations in target detection ability at a similar frequency on *uncued* objects, though typically at a different oscillatory phase (i.e., when target detection ability is high for the cued object it is low for the uncued object and vice versa) (Fiebelkorn et al., 2013; Jia et al., 2017; Landau and Fries, 2012). This suggests that the focus of attention periodically shifts to uncued objects as part of an ongoing monitoring process. Neither the spread of attention across cued objects nor this ongoing monitoring of uncued objects have previously been investigated in schizophrenia, to our knowledge.

In the present study, we addressed these gaps in knowledge about both the presence of attentional oscillations and the dynamics of object-based attention in schizophrenia. To do so, we adapted a canonical performance-based behavioral paradigm originally used to investigate the rhythmic properties of object-based attention in healthy individuals, which probes fluctuations in target detection ability at several target locations relative to a set of

visual objects (Fiebelkorn et al., 2013). Based on known deficits in attention and object perception in schizophrenia, we hypothesized that object-based attention would be abnormal in the disorder. In particular, we predicted that the amplitude (i.e. strength) of object-based attentional oscillations would be reduced in schizophrenia at one or more of the target locations.

2. Methods

2.1. Participant recruitment and characterization

A sample of 30 participants with a DSM-5 diagnosis of schizophrenia and 20 healthy controls were enrolled in the study. The schizophrenia sample was comprised of stable adult outpatients from the Los Angeles area. Members of the control group were selected to have a similar age, parental education, and gender distribution to the schizophrenia group. All participants were required to have normal or corrected-to-normal visual acuity. Detailed inclusion and exclusion criteria are listed in the Supplemental Methods (Supplement 1.1).

All participants completed an interview that included questions about demographics and medical history, the updated version of the Structured Clinical Interview for DSM-5 (SCID-1) (First et al., 2015), the Expanded Brief Psychiatric Rating Scale (BPRS) (Overall and Gorham, 1962), and the Clinical Assessment Interview for Negative Symptoms (CAINS) (Kring et al., 2013). Controls also completed the SCID-PD (First et al., 2015). All interviews were conducted by masters- and doctoral-level raters trained through the Treatment Unit of the Department of Veterans Affairs Desert Pacific Mental Illness Research, Education, and Clinical Center to a minimum kappa of 0.75 for psychotic and mood items (Ventura et al., 1998). To corroborate self-report information, medical records and clinician notes were considered, if available.

2.2. Experimental Design and Procedure

The experimental task used in this study was adapted from a paradigm developed by Fiebelkorn and colleagues (2013) to study the spatiotemporal dynamics of object-based attention. In this paradigm, an attentional cue (luminance change) appears in one of several locations on each trial, after which a target (faint Gabor patch) appears in either the same location (valid cue trial), a different location (invalid cue trial), or not at all (catch trial). Participants are simply asked to fixate continuously on a central point and indicate the presence or absence of the target after each trial.

Unlike a generic attentional cueing task, in this paradigm the cue and target locations are always at the ends of a pair of parallel rectangular objects (see Figure 1). Two types of invalid cue trials can occur: same-object invalid cue trials (where the target appears at the opposite end of the same rectangle) and different-object invalid cue trials (where it appears at the same distance from the cue, but on the other rectangle). Crucially, the inter-stimulus interval (ISI) between the cue and target is randomly varied in precise increments of 10ms from 300–800ms. This variation in the cue-target ISI allows for an attentional timecourse (i.e., accuracy by ISI) to be characterized separately for each trial type. For

details about task implementation (e.g., equipment, stimulus sizes), see the Supplemental Methods (Supplement 1.2).

Once participants were seated at the computer, the task was explained to them, example stimuli were shown, and they had an opportunity to practice during a brief tutorial. Next, the threshold contrast of the target Gabor was determined for each participant using a staircase procedure (see Supplement 1.3). The main task, which followed, consisted of five blocks, each containing 384 trials (i.e. 1920 trials total). Participants were prompted to take a short break after every 100 trials within each block, and they were offered longer breaks between blocks. Within each block, 25% of all trials were catch trials (i.e., target-absent trials). The catch trials were necessary to allow for Signal Detection Theory (SDT) measures (e.g., d') to be calculated from the data. On target-present trials, the target appeared at the cued location 75% of the time. However, the target appeared at the other end of the *same* object on 12.5% of target-present trials, and the same distance from the cue on the end of the *other* object 12.5% of the time (see Figure 1). Participants received auditory feedback indicating whether each response was correct. While the proportion of trials in each condition was fixed within each block, the ISI for each trial varied randomly on each trial in 10ms increments within the ranges shown in Figure 1 (50 total ISI levels). Thus, over the course of the entire experiment, targets appeared an average of 21.6 times per 10ms ISI level at the cued location and 3.6 times per level each for the same-object and other-object locations, though the exact number of targets per bin in each condition varied from subject to subject due to the random ISI selection.

2.3. Data Analysis

2.3.1. Signal Detection Theory.—Accuracy data were first examined to determine how well participants distinguished target-present versus target-absent trials. Specifically, we calculated d' for each participant across all task conditions using the formula Z(Hit Rate) – Z(False Alarm Rate). Because the target intensity was titrated for each individual participant, all participants should have been able to detect the target reliably but not easily, which would result in modest but positive d' scores of similar magnitude across groups. Negative d' scores (i.e., more frequent false alarms than hits) are thus a clear marker of an invalid response pattern. Participants were therefore excluded from all subsequent analyses if they did not have a d' score that exceeded zero. We tested for differences in d' between included participants from the two groups using Welch's t-test, which is robust to potential inequalities in group variance.

2.3.2. Fourier Analysis.—Accuracy data (i.e., hit rates) from the three target-present conditions were next examined in the time domain using Fourier decomposition, in order to characterize the amplitude of attentional oscillations across a spectrum of frequencies. For condition, for each subject, mean accuracy was first calculated at every possible cue-probe interval (i.e., 10ms increments from 300–800ms). Next, missing values, which occurred sporadically when a particular ISI was not tested in a condition due to the randomization method, were linearly interpolated, and then each timecourse was smoothed using a 5-bin moving average with re-centered output. These timecourses were linearly detrended and zero-padded at the beginning and end. We then calculated the mean timecourse across all

participants within each group for each condition. Those mean timecourses were multiplied by a Hanning window of the same length, after which a Fast Fourier Transform (FFT) was applied. The resulting values capture the amount of fluctuation in task accuracy at specific oscillatory frequencies (by group and condition).

Because of the timing parameters used in the experiment, this approach yielded a measure of the amplitude of attentional oscillations in each group and condition for frequencies between 0 and 50Hz in increments of approximately 2.17Hz. Since attentional oscillations are typically found at low (~4–10Hz) frequencies in healthy samples, we limited our window of interest for statistical comparisons to the 2.17–19.57Hz range (allowing for potential group differences at harmonics of the expected oscillatory frequencies).

2.3.3. Bootstrap tests.—To test for statistically significant oscillatory effects of attention within and between groups, we used a bootstrapping approach similar to previous studies (Fiebelkorn et al., 2013). Specifically, for one-sample tests (i.e., to determine if significant oscillations in accuracy existed for a given group and condition), we generated null distributions of oscillatory amplitude for each group and condition, at each frequency, by randomly reshuffling each corresponding timecourse and calculating a new FFT across 10,000 iterations, then sorting the resulting amplitude scores to form a null distribution. In order to correct for the number of tests performed, we Bonferroni-corrected our statistical alpha to 0.008 (i.e., 0.05 ÷ 6).

We used an equivalent bootstrapping approach to test for group differences by condition and frequency. For each experimental condition, we calculated the actual (observed) difference in oscillatory amplitude between the schizophrenia and control groups, across all frequencies of interest. Then, across 10,000 iterations, we shuffled group labels among all participants and performed full FFT analyses within the resulting random groups (which contained the same number of participants as the original groups). Within each iteration, we calculated the rectified amplitude difference between the two randomly assigned groups for each condition at each frequency. These difference scores were sorted to create a set of null distributions for each experimental condition, across all frequencies of interest. To identify significant group differences, we compared the observed group differences with the null distribution. In order to correct for the number of tests performed, we Bonferroni-corrected our statistical alpha to 0.016 (i.e., 0.05 ÷ 3).

3. Results

3.1. Participant Characteristics

As noted in Section 2.4.1, we conducted an initial validity check of the data based on d' scores. Ten members of the schizophrenia group and five members of the control group who had d's less than or equal to zero (d' range: −1.70 – 0.0), indicating a pattern of invalid responses across task conditions, were excluded from all subsequent analyses. For the remaining participants, the schizophrenia group had a mean d' of 0.75, and the control group had a mean d' of 0.67. This difference did not differ significantly between the groups, $t(30.78) = -0.36$, $p = 0.72$. We performed additional analyses to explore possible effects of participants who had low but positive d' scores, which are reported in the Supplement.

Demographic characteristics of the included participants by group are detailed in Table 1. We performed Welch's *t*-tests to check for group differences in demographics (except gender, for which we used a chi-squared test). Overall, the groups were well matched for age, gender, and parental education; there were no significant group differences for any of these characteristics. As expected, controls had more years of personal education than the schizophrenia group $t(22.01) = 2.97$, $p = 0.007$. Members of the schizophrenia group had relatively mild clinical symptoms. For the BPRS, the mean positive symptom score was 1.99 (standard deviation = 0.92). For the CAINS, the mean experiential negative symptom rating was 1.87 (0.80), and the mean expressive negative symptom rating was 1.30 (0.93).

To determine whether there were any differences in the characteristics of the included participants versus those excluded because of low d' scores, we performed a series of tests. For personal education, an ANOVA with factors 'participant group' and 'exclusion status' yielded a significant main effect of participant group (i.e., controls vs. schizophrenia), capturing the expected difference in personal education between the schizophrenia and control participants ($F(1,45) = 4.64$, $p = 0.04$). However, there was no main effect of exclusion status ($F(1,45) = 1.77$, $p = 0.19$) nor a participant group by exclusion status interaction ($F(1,45) = 0.98$, $p = 0.33$). Similar ANOVAs for participant age and parental education showed no significant main effects or interactions (all *p*-values > 0.4). A chi-squared test showed no significant difference in the gender distribution of the included vs. excluded participants. Within the schizophrenia group, Welch's *t*-tests showed no significant differences in BPRS or CAINS scores between the included and excluded participants (all *p*-values > 0.25).

3.2. Mean Accuracy, collapsed across ISIs

Overall accuracy scores by group and condition, collapsed across ISIs, are presented in Table 2. To test for overall effects of group and condition on accuracy, we performed a mixed-design ANOVA with group as a between-subjects factor and condition as a within-subjects factor. This analysis showed a significant main effect of condition ($F(3,99) = 11.17$, $p < 0.001$), with the highest accuracy in the cue location condition, the lowest accuracy in the catch trial condition, and similarly intermediate accuracy for the cued and uncued object conditions (see Table 2). Poorer performance in the catch trial condition was expected because there are relatively few target-absent trials relative to target-present trials. Follow-up pairwise comparisons showed significant differences between all condition pairings except cued vs. uncued objects. There was no significant main effect of group on overall accuracies ($F(1,33) = 0.10$, $p = 0.75$), nor a significant group by condition interaction ($F(3,99) = 0.20$, $p = 0.90$).

3.3. Oscillatory Analyses

Fluctuations in target detection accuracy over time, as a function of group and condition, are depicted in Figure 2. All statistical analyses focused on the Fourier spectra of these timecourses (see Section 2.4.2). Those spectra are depicted in Figure 3 (black lines). Within-group bootstrap analyses identified various frequency bands in which significant attentional oscillations were present for each condition. For the cued location, both groups showed significant attentional oscillations in the 2.17–4.35 Hz frequency range (see Figure 3). For

the cued object condition, controls had significant oscillations in the 4.35 – 8.70 Hz range, but the schizophrenia group had no significant oscillations (see Figure 3). For the uncued object condition, the control group had significant oscillations in the 2.17–4.35 Hz range, as well as at 10.87 Hz, but the schizophrenia group only had significant oscillations at 4.35 Hz (see Figure 3).

Between-group bootstrap analyses of oscillatory amplitude showed several significant differences between schizophrenia and controls. For the cued location, oscillations in the schizophrenia group had a significantly greater amplitude than in the control group for the 2.17–4.35 Hz frequency range (see Figure 4). For the cued object location, oscillations in the control group had a significantly greater amplitude than in the schizophrenia group for the 6.52–8.70 Hz range (see Figure 4). For the uncued object condition, oscillations in the control group had a significantly greater amplitude than in the schizophrenia group only in the 10.87 Hz band (see Figure 4).

4. Discussion

These results establish for the first time that oscillations in sustained object-based attention are present in schizophrenia. Effects in the control group mostly replicated findings from previous studies that focused exclusively on healthy samples, although in our dataset the oscillatory activity at the cued location peaked at a lower frequency than in some previous studies (about 4Hz instead of about 8Hz). The pattern of attentional oscillations that emerged from the schizophrenia group was similar in some respects; the schizophrenia group also showed significant oscillations in target-detection ability at a relatively slow rate of about 2–4 Hz.

However, we found clear differences between the schizophrenia and control groups in other respects. Higher-frequency oscillations in object-based attention that were present in controls for the range of about 6–10 Hz did not emerge in the schizophrenia sample. For lower-frequency oscillations, the oscillatory signature of attention was stronger in schizophrenia than in controls for the cued location, essentially absent in schizophrenia for the cued object condition, and not statistically different between groups for the uncued object condition. Overall, these results suggest there are substantial abnormalities in object-based attention among individuals with schizophrenia.

Two aspects of the results are particularly striking. First, at the cued location, the oscillatory signature of attention was actually stronger in schizophrenia than in controls, which is consistent with the schizophrenia group having allocated more attention than controls to the cued location. Second, at the opposite end of the cued object (where oscillations are strongest in controls), the oscillatory signature of attention was absent in schizophrenia, which shows that the defining process of object-based attention – the rapid and automatic spread of attention across object surfaces – fails to occur reliably in schizophrenia. Together, these two effects suggest that attention remains hyperfocused at the spatial location of the cue in schizophrenia. This is highly consistent with a recent theory that attributes spatial attention deficits in schizophrenia to hyperfocusing (Hahn et al., 2021; Kreither et al., 2017; Luck et al., 2019, 2014). Our findings suggest that deficits in object-based attention

among individuals with schizophrenia may also be fundamentally related to attentional hyperfocusing.

Although the present results offer key insights into specific attentional deficits in schizophrenia, the current study had several notable limitations. The number of participants was relatively small. Also, the task we used was quite difficult, and about a third of participants in each group were excluded because they had d' scores that did not exceed zero, indicating an invalid response pattern. However, there were no significant differences between the included and excluded participants in terms of demographics or clinical symptoms, suggesting that the characteristics of the included and excluded participants were similar. Based on examination of trialwise response patterns, most of the participants with negative d' scores appear to have adopted a strategy of responding at random or giving the same response on nearly all trials. This could have occurred because those participants felt like they were guessing, which is somewhat expected for this type of task. One future solution for this problem might be to set the pre-experimental target intensity titration to an easier threshold level so that participants feel like they are guessing less often, although this change would probably require more experimental trials. Another important limitation of the present study is that the participant samples were relatively homogenous groups of older adults who were predominantly male, and the schizophrenia group was comprised of stable outpatients on clinically determined doses of medication who had relatively mild positive and negative symptoms. To establish the generalizability of the findings, it will be important for future studies to recruit larger and more diverse samples. Finally, some very recent publications (e.g., Fiebelkorn, 2021; Brookshire, 2022) have raised questions about assumptions of phasic consistency and periodicity in the attentional oscillation literature to date, which have shaped the interpretation of effects such as ours. Since our experimental paradigm was not designed to be sensitive to trialwise phase effects, and to maximize comparability of our results to published findings in the non-clinical literature, we chose to retain the common assumptions of consistent phase and periodicity in the current study, and our analytic approach reflects this. However, we plan to explore questions of phase and periodicity using EEG data from a related attentional paradigm that is better suited to addressing such issues in a future paper (Reavis, Wynn, & Green, In Preparation).

Nevertheless, the present results provide the first evidence of attentional oscillations in schizophrenia, as well as the first evidence of a specific deficit in object-based attention in the disorder. Furthermore, our findings appear to extend the theory of attentional hyperfocusing in schizophrenia into a new domain of visual cognition: object-based attention. These previously overlooked phenomena may be important for understanding perceptual deficits in schizophrenia more broadly. Thus, the present study offers an important starting point for further investigation of object-based attention and attentional oscillations in schizophrenia and related disorders.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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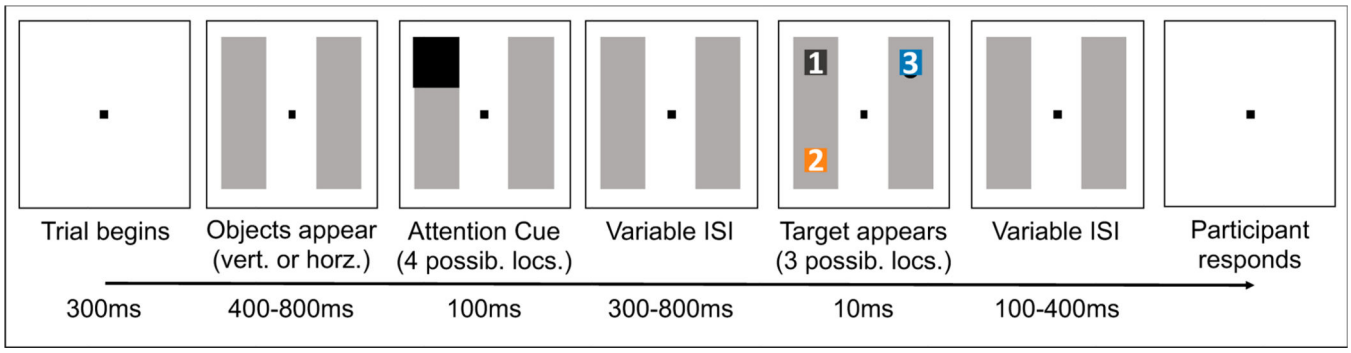

Figure 1.

Trial schematic, with time durations. Stimuli are not drawn to scale. Cue location was randomized to one of the four rectangle-end locations across trials, and target locations were determined based on the location of the cue.

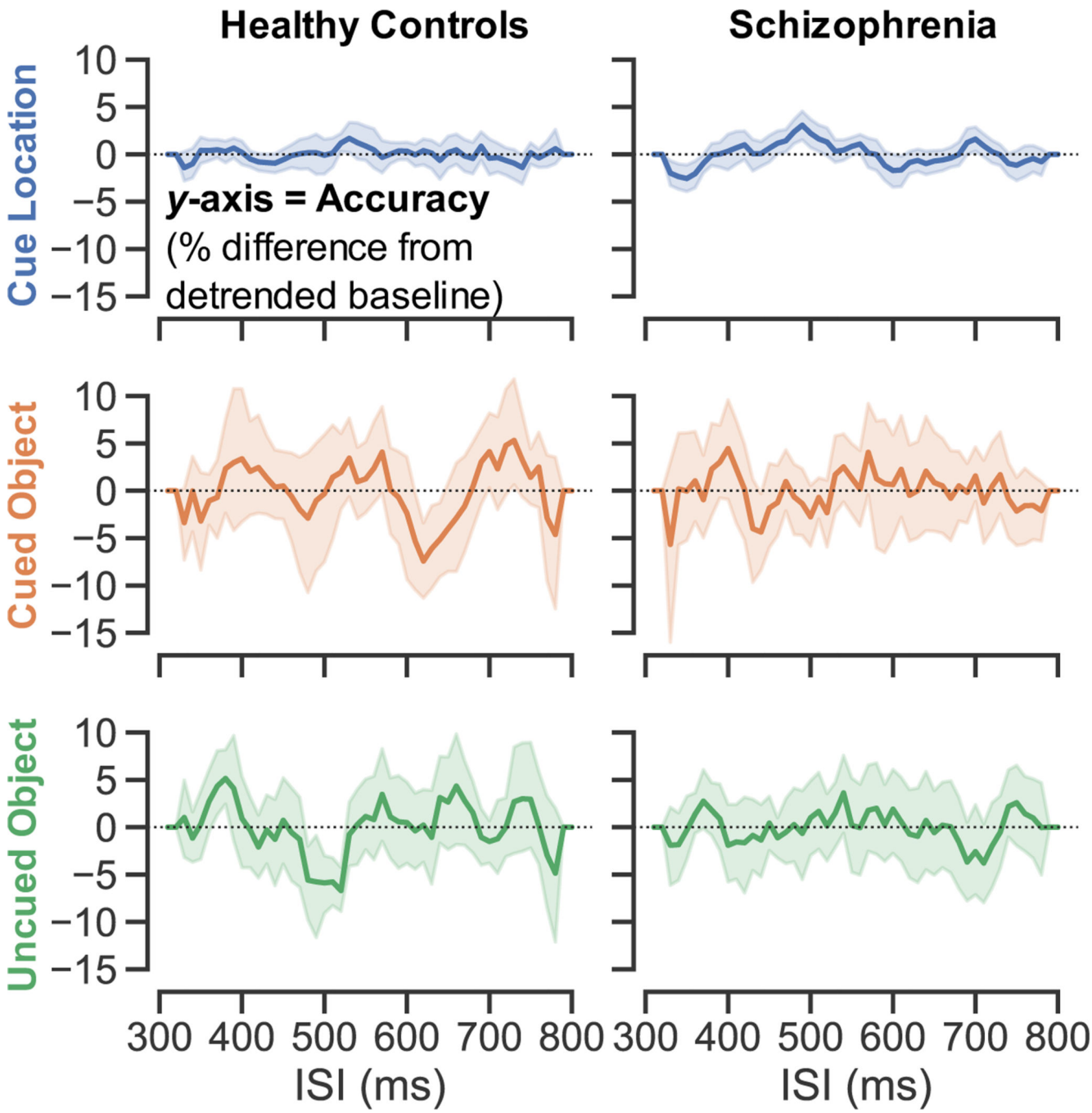

Figure 2.

Time-domain data: Attentional oscillations by condition and group. Plotted lines depict smoothed, detrended target detection accuracy (i.e., percentage accuracy difference from detrended baseline) as a function of time since the attentional cue (see Section 2.4.2). Error bands depict 95% confidence intervals.

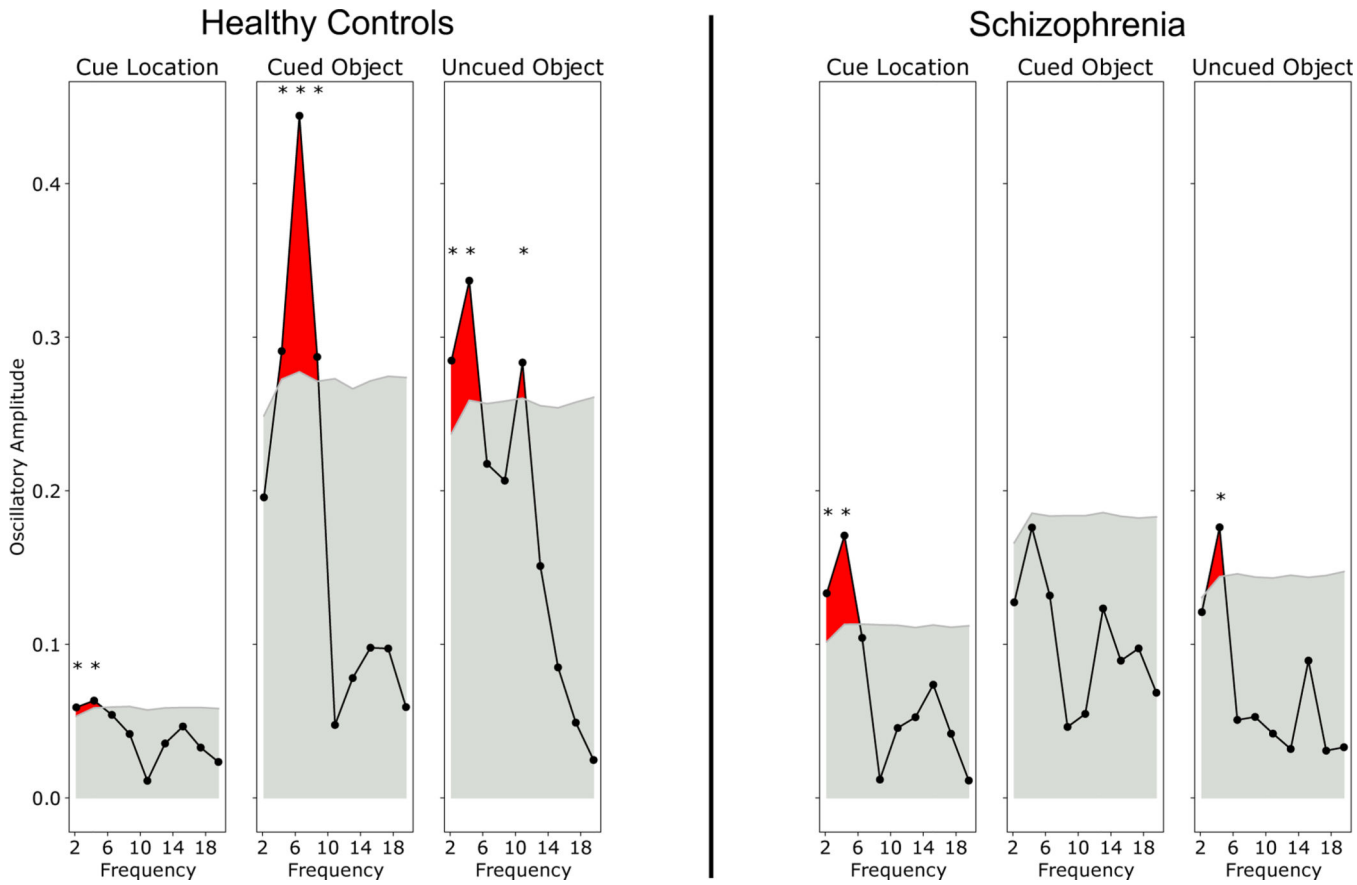

Figure 3.

Frequency-domain data: Within-group attentional oscillations. The black line corresponds to the observed amplitude of attentional oscillations for each condition and frequency, by group (i.e., the Fourier spectrum of the curves plotted in Figure 2, for the frequency range of interest). The grey shaded area corresponds to the $p<0.008$ threshold amplitude of the bootstrapped null distribution (see Section 2.4.3); areas where observed oscillation amplitudes significantly exceeded the bootstrapped threshold are shaded in red. Stars indicate specific frequency bands where effects were significant.

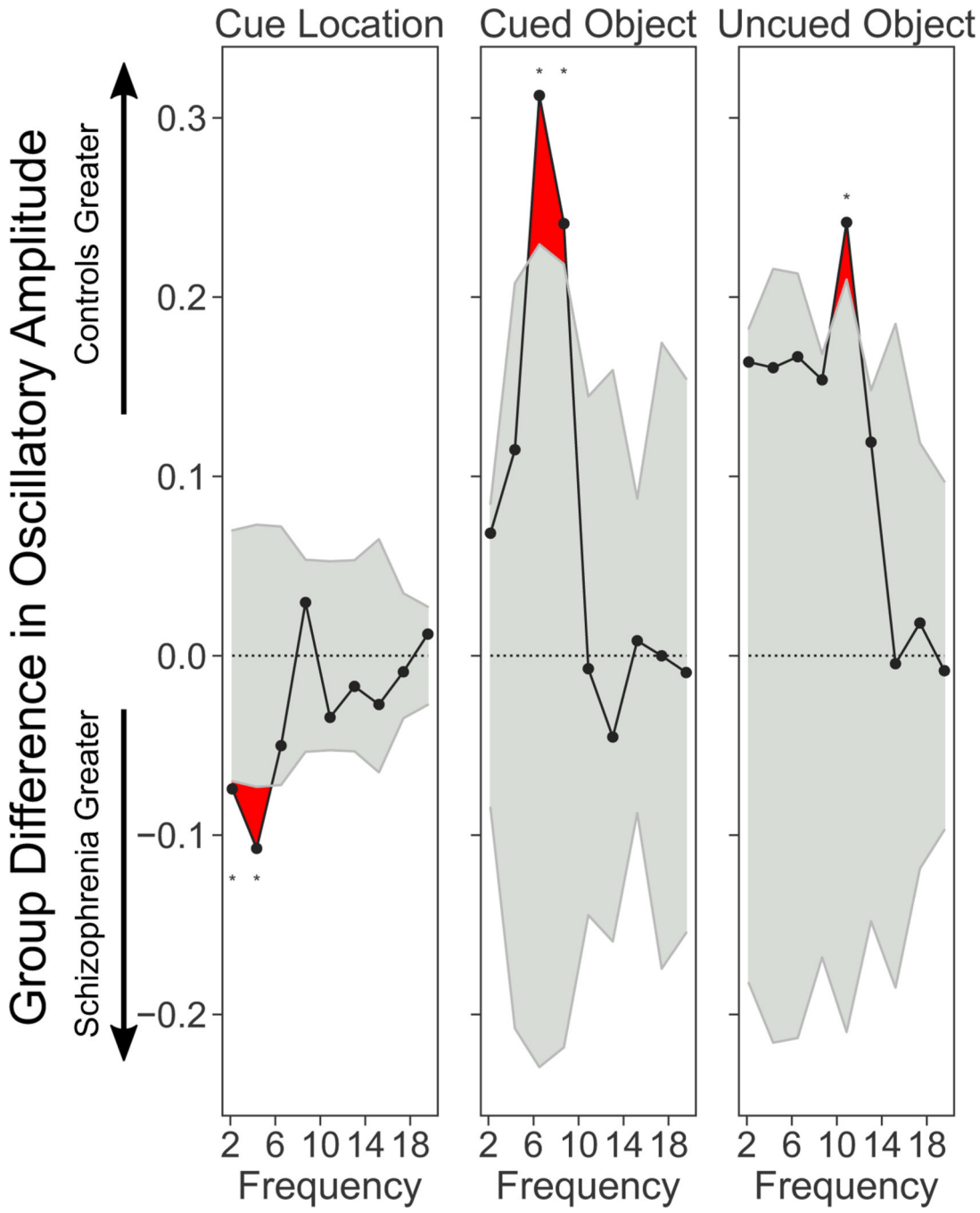

Figure 4.

Frequency-domain data: Between-group differences in attentional oscillations. The black line corresponds to the difference in oscillatory amplitude between the schizophrenia and control groups, by condition and frequency. Values above zero represent higher amplitude oscillations in controls; values below zero represent higher amplitude oscillations in schizophrenia. The grey shaded area corresponds to the $p<0.016$ threshold amplitude of the symmetrical bootstrapped null distribution (see Section 2.4.3); areas where observed

group differences in oscillation amplitudes significantly exceeded the bootstrapped threshold are shaded in red. Stars indicate specific frequency bands where effects were significant.

Table 1:

Participant Demographics.

Parenthetical values are standard deviations.

	Schizophrenia	Controls
Sex (M/F)	12 / 8	12 / 3
Age (Years)	48.5 (11.6)	47.5 (7.3)
Personal Education (Years)	13.1 (1.3)	15.0 (2.2)
Parental Education (Mean Years)	13.1 (2.1)	14.3 (3.1)

Table 2:

Mean percentage of trials correct, by group and condition.

Means (standard error of the mean) are collapsed across all ISIs.

Target Position:	Cue Location	Cued Object	Uncued Object	Catch Trials
Schizophrenia	83.7% (3.0%)	57.3% (6.2%)	60.5% (6.0%)	48.3% (6.0%)
Controls	84.3% (3.6%)	61.1% (8.0%)	56.0% (8.1%)	43.5% (8.5%)