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Prolonged temporal interaction for peripheral visual processing in schizophrenia: Evidence from a three-flash illusion

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ABSTRACT

Background: Coherent perception of the visual world requires orderly processing of spatially and temporally distributed visual information across the visual field. The organization of this visual information is impaired in schizophrenia. We previously found that visual temporal integration in patients is prolonged, using flashes presented to the central fovea. In this study, we investigated this temporal interaction in both the fovea and fairly far out in the peripheral visual field.
Methods: We used a 'three-flash' illusion paradigm in which two spatially-coincident light pulses (of 1 ms each) are perceived by healthy individuals as one, two or three flashes depending on the time interval between the pulses. In each trial, two light pulses were presented in the fovea or 34° out in the right visual field. The inter-stimulus pulse interval (ISI) ranged from 30 to 310 ms. The task for patients ($n = 28$) and controls ($n = 26$) was to indicate the number of flashes (one, two or three) perceived after each two-pulse presentation.
Results: For the controls, the peak of the three-flash illusion was shifted to longer ISIs (150 ms) in the periphery compared to the fovea (110 ms). For the patients, the three-flash illusion was greater and occurred at longer ISIs (270 ms in the periphery and 190 ms at the fovea).
Conclusion: Compared to the central visual field, the range of temporal interactions in the periphery is prolonged to a greater extent in schizophrenia. This exacerbated temporal expansion in peripheral vision suggests a coarse temporal resolution for visual and cognitive organization in this mental disorder.

1. Introduction

The cardinal symptom of schizophrenia is disorganized thought and behavior, but we know much less about the basic perceptual and cognitive mechanisms that potentially contribute to this disorganization. Schizophrenia patients have deficient processing of visual signals (Green et al., 2009; Butler et al., 2012; Silverstein and Keane, 2011). To provide sensory inputs for coherent thoughts and behaviors, visual processing must integrate spatially and temporally distributed information. This integration requires that visual information is gathered from large regions of the visual field, often well outside of the fovea.

Understanding this spatiotemporal integration in schizophrenia may shed light on where visual integration begins to fall apart. There are a number of studies done in the fovea on deficient processing of dynamic visual information in schizophrenia (O'Donnell et al., 1996; Stuve et al., 1997; Chen et al., 1999a, 1999b, 2003; Carroll et al., 2008; Norton et al., 2008; Chen, 2011; Parsons et al., 2013). But surprisingly little is known about these processes in the peripheral field, where global and dynamic visual signals are preferentially processed.

Visual processes have different spatial and temporal characteristics in the central vs. peripheral fields. The periphery has a coarse resolution for processing spatial information. But for processing temporal information, the periphery appears to have a higher resolution than does the fovea, as shown in several ways. First, critical fusion frequency (CFF), or the highest flicker rate resolvable, increases towards the periphery (Hartmann et al., 1979; Nakayama and Tyler, 1981). Second, temporal contrast modulation sensitivity extends to higher temporal frequency (McKee and Taylor, 1984; Allen and Hess, 1992). Third, temporal resolution as measured by the minimum perceivable temporal gap between two light pulses increases with eccentricity (provided that the spatial size of the stimuli is scaled larger at greater eccentricity to compensate for cortical magnification) (Poggel et al., 2006). The periphery thus responds better than the fovea to larger spatial objects and faster temporal changes. These spatial and temporal properties allow visual processing in the periphery to serve as a rough spatial guide but a fine

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temporal meter to alert about major changes in the part of visual world that is not the current focus of attention.

Several studies have examined peripheral visual processing in schizophrenia, using either detection tasks or search tasks that engage multiple target positions. Two of the studies (Granholm et al., 1996; Elahipanah et al., 2010) showed that patients had degraded performance for detecting peripheral visual targets, but another study (Miller et al., 1990) showed relatively intact visual detection in periphery. Interestingly, under backward masking conditions, both patients (Green et al., 1994a; Butler et al., 1996) and their siblings (Green et al., 1997, 2006; Sponheim et al., 2013) showed impairments in perception of the target location and target identification, with the targets presented at multiple possible peripheral locations. The impaired performances occurred primarily when temporal intervals between target and mask were brief (20 to 80 ms). These masking results are consistent with the notion that spatial and temporal processing in schizophrenia is altered within the peripheral field.

There are two critical issues regarding these studies on peripheral visual processing in schizophrenia. First, there was no direct comparison of temporal processing in the periphery versus fovea (Green et al., 1994b; Norton et al., 2008). Second, there was a possible confounding effect of spatial uncertainty, since the targets were presented into multiple possible spatial locations (Green et al., 1994b; Kraehenmann et al., 2012). The impaired performance might thus partly reflect difficulties of attending to many targets/locations at once. In the present study, we directly compare visual temporal processing in the fovea versus periphery, using a single stimulus that removes the problem of spatial uncertainty.

In an earlier study, we measured temporal interactions in the fovea in schizophrenia patients using the three-flash illusion paradigm (Norton et al., 2008). In this paradigm, two brief light pulses are sequentially presented in the same position, and the perception is that of either 1, 2 or 3 flashes. The three-flash illusion refers to the perception of three flashes while only two light pulses are presented (Bowen, 1989). The number of flashes perceived is presumably determined by the interaction between the two separate temporal impulse response functions (IRF) generated by each of the two light pulses. The response to the light pulses provide information about the functional role of the IRF and the integration of the two IRFs produced by the two pulses (see Discussion), which include both linear and non-linear temporal processing of the visual system.

Our foveal study of three-flash illusion suggests that patients have prolonged temporal responses. In the present study, we compared the three-flash illusion in the fovea versus periphery, using both patients and healthy controls. Our working hypothesis is that the three-flash illusion 1) will occur at shorter ISIs for peripheral than for foveal targets (assuming that temporal processing is relatively fast in periphery), and 2) will occur at longer ISIs for patients than for controls (assuming that sluggish temporal processing is implicated in schizophrenia).

2. Methods and materials

2.1. Subjects

Twenty-eight patients and 26 non-psychiatric controls participated in this study. The patients met criteria for schizophrenia or schizoaffective disorder based on an interview by independent clinicians using the SCID-IV (First et al., 2002) and all available medical records. The clinicians were trained research assistants, psychologists, and psychiatrists. The patients were either inpatients from the Schizophrenia and Bipolar Disorders Program at McLean Hospital ($n = 6$) or were outpatients who received treatment from McLean Hospital or local clinics ($n = 22$). Fourteen of the patients had the diagnosis of schizophrenia and the other fourteen had the diagnosis of schizoaffective disorder (eight were bipolar-type and the other six were depressive-type). All patients were taking antipsychotic medication (mean chlorpromazine equivalent was 537.2 mg (SD: 358.1 mg) (Davis, 1974; Woods, 2003). Their average duration of illness was 18.0 years (10.4 years). The patients' PANSS scores for the positive, negative and general scales ranged from 7 to 29 (mean: 15.8 (6.8)), 7 to 30 (mean: 13.6 (5.9)) and 16 to 48 (mean: 29.4 (10.6)), respectively.

Healthy controls were screened for Axis 1 disorders using an interview based on the SCID N/C (First et al., 2002). Patients and controls were excluded if they had recent (6 months) drug or alcohol abuse, or a history of brain injury or neurological disorders (such as seizure or stroke). The protocol was approved by Mclean Hospital Institution Review Board. All subjects signed informed consent in accordance with the IRB guidelines.

Demographic information is provided in Table 1. Patients and controls did not differ in age or sex. The groups were significantly different in terms of education ($t = 2.4$, $p = 0.02$) and IQ ($t = 2.3$, $p = 0.02$). Visual acuity of the participants was shown to be normal using the Rosenbausm Pocket Eye Chart. The same groups of subjects had participated in our previous foveal study (Norton et al., 2008) but were tested for this study in a peripheral visual field as well as at the fovea with briefer light pulses (see below).

2.2. Procedure

2.2.1. Light pulses

Light pulses were generated with a red light emitting diode (LED) which allows precise temporal control within the micro-second range. A Macintosh G3 system controlled the visual stimuli and recorded the subject's responses. On each trial, light pulses of 1 ms were presented twice, with an inter-stimulus interval (ISI) of either 30, 70, 90, 110, 130, 150, 190, 230, 270 or 310 ms (Fig. 1). There were 100 trials for the periphery and 100 trials for the fovea, with 10 trials devoted to each ISI in a quasi-random order. The whole procedure lasted 20 to 25 min.

The LED was a nearly uniform disc (subtending 17 min arc) with a peak luminance 35 cd/m^2. In separate runs, the LED target was presented at the fovea and the 34° right visual field (i.e. at 45 cm from fixation at a viewing distance of 66.7 cm).

2.2.2. Task

The LED target was viewed in a dimly-illuminated room. A fixation point was provided for the eccentric LED target. The fixation target was visible at all times and thus could be fixated well.) Subjects were instructed to press a button to initiate the presentation of the pulses, when they were fixating well. Under all conditions the pulse was clearly visible at a relatively high suprathreshold level. As discussed earlier, all subjects were well practiced in the task. The subject on each trial pressed buttons to indicate whether they saw 1, 2 or 3 flashes.

The dependent variable here was the perceived flash number in each trial.

3. Results

3.1. Three-flash illusion at the fovea and in periphery

The three-flash illusion differs significantly between patients and controls (Fig. 2). A three way ANOVA (group × ISI × field) of 3 flash data showed significant effects on group ($F = 19.8$, $p < 0.001$) and ISI ($F = 14.5$, $p < 0.001$), but not on field ($F = 0.000$, $p = 0.98$). The interaction was significant between ISI and field ($F = 7.06$, $p < 0.001$), but not between group and ISI ($F = 2.37$, $p = 0.12$) or between group and field ($F = 0.48$, $p = 0.49$). The three way interaction was not significant ($F = 0.21$, $p = 0.99$).

This analysis indicates that three-flash illusion differs between patients and controls but difference similarly occurs at the fovea and in the periphery (Fig. 2). A combination of the absence of interactions between group and ISI or between group and field and the presence of