Schizophrenia is often accompanied by a range of visual perception deficits, with many involving impairments in motion perception. The presence of perceptual abnormalities may impair neural processes that depend on normal visual analysis, which in turn may affect overall functioning in dynamic visual environments. Here, we examine the integrity of suppressive center-surround mechanisms in motion perception of schizophrenic patients. Center-surround suppression has been implicated in a range of visual functions, including figure-ground segregation and pursuit eye movements, visual functions that are impaired in schizophrenia. In control subjects, evidence of center-surround suppression is found in a reduced ability to perceive motion of a high-contrast stimulus as its size increases. This counterintuitive finding is likely a perceptual correlate of center-surround mechanisms in cortical area MT. We now show that schizophrenic patients exhibit abnormally weak center-surround suppression in motion, an abnormality that is most pronounced in patients with severe negative symptoms. Interestingly, patients with the weakest surround suppression outperformed control subjects in motion discriminations of large high-contrast stimuli. This enhanced motion perception of large high-contrast stimuli is consistent with an MT abnormality in schizophrenia and has a potential to disrupt smooth pursuit eye movements and other visual functions that depend on unimpaired center-surround interactions in motion.

Key words: schizophrenia; perception deficit; visual motion; center-surround; inhibition; negative symptoms

Introduction

Schizophrenia is associated with a number of abnormalities in visual perception, including deficits of visual backward masking (Green and Walker, 1986; Schechter et al., 2003), luminance flicker sensitivity (Slaghuis and Bishop, 2001), biological motion perception (Kim et al., 2005), and velocity discrimination (Chen et al., 1999a). Visual deficits in schizophrenia often share a common thread: abnormalities are found in perceiving moving and/or dynamic stimuli, stimulus conditions implicating impairments of the magnocellular (transient) visual processing stream (Butler and Javitt, 2005). This broad class of deficits may cascade into impaired functioning in dynamic visual environments. Moreover, other brain functions that rely on transient information processed by the visual system may also be jeopardized. One notable example is the smooth pursuit eye movement (SPEM) deficit, present in a majority of schizophrenic patients. This deficit is expressed as an abnormally low pursuit gain and frequent saccadic intrusions (Holzman et al., 1973). The magnitude of SPEM deficit is correlated with the motion perception abnormalities (Chen et al., 1999b,c; Slaghuis et al., 2005), suggesting a possible link between two deficits.

Intimately involved in cortical motion processing are visual areas MT and MST (Orban, 1997; Born and Bradley, 2005), key brain areas in the magnocellular stream. It is natural to speculate, therefore, that areas MT/MST may be abnormal in schizophrenia (Chen et al., 2003a). However, it is yet unclear what mechanisms underlie this deficit. One functional role of MT is representation of both object and background motion (Born and Bradley, 2005). This dual coding of motion can be linked to two types of MT neurons: antagonistic center-surround neurons, which have inhibitory surrounds and respond best to small moving objects, and wide-field neurons, which lack inhibitory surrounds and prefer large moving fields (Allman et al., 1985; Born and Tootell, 1992). Furthermore, microstimulation of MT sites with center-surround neurons shifts SPEM in the direction similar to the preferred direction of the stimulated clusters of neurons (Born et al., 2000), suggesting that center-surround neurons encode object motion. In contrast, microstimulation of MT sites with wide-field neurons shifts SPEM in the direction opposite to the preferred direction of the stimulated neurons, suggesting that wide-field neurons encode background motion. Thus, any abnormality of center-surround interactions has a potential to disrupt normal SPEM.

In human vision, antagonistic center-surround interactions are revealed by the reduced ability to perceive motion as the size of a moving stimulus increases (Tadin et al., 2003; Paffen et al., 2006). This observation suggests the presence of suppressive surround mechanisms. Moreover, both behavioral (Tadin et al., 2003) and neurophysiological (Pack et al., 2005) investigations
have shown that surround suppression only occurs with high-contrast stimuli. Thus, investigating perceptual center-surround interactions in motion perception should elucidate the integrity of neural center-surround interactions (Tadin and Lappin, 2005) and contribute to our understanding of motion perception deficit(s) in schizophrenia. In the context of schizophrenia, abnormal center-surround interactions would suggest the involvement of cortical area MT in those abnormalities.

### Materials and Methods

#### Motion discrimination experiment

**Subjects.** Sixteen patients (four females) who met the Diagnostic and Statistical Manual of Mental Disorders IV (DSM-IV) criteria for schizophrenia were recruited from an outpatient treatment facility in Nashville, TN. Their diagnosis was determined from the Structured Clinical Interview for DSM-IV (Spitzer and Williams, 1985). The mean age of the patients was 35.9 years (SD, 8.8 years), mean education level was 12.9 years (SD, 1.9 years), and they had been ill for an average of 13.4 years (SD, 7.1 years). All patients were on atypical antipsychotic medication at the time of the experiment. Mean chlorpromazine equivalent (CPZ) dose was 325 mg/d (SD, 192). Clinical symptoms were assessed with the Brief Psychiatric Rating Scale (BPRS) (Overall and Gorham, 1962), the Scale for Assessment of Positive Symptom (SAPS) (Andreasen and Olsen, 1982), and the Scale for Assessment of Negative Symptom (SANS) (Andreasen and Olsen, 1982). Mean scores for BPRS, SAPS, and SANS were 22.5, 18, and 28.5, respectively. Median scores for BPRS, SAPS, and SANS were 22.5, 18, and 28.5, respectively (Table 1).

Fourteen healthy control subjects (six females) with no history of mental illness or neurological disorders were recruited from the community. Their mean age was 35.5 years (SD, 7.2 years), and their mean education level was 14.3 years (SD, 1.9 years). Normal control subjects were screened to rule out schizotypal personality using the Schizotypal Personality Questionnaire (SPQ) (Raine, 1991) before the experiment. No control subject scored high on the SPQ; the mean score on the SPQ was 70.4 (SD, 56.1) for schizophrenia and 10.7 (SD, 6.2) for control subjects. Mean ages of control and schizophrenic subjects were 35.9 years (SD, 7.1 years) and 35.5 years (SD, 7.2 years), respectively. All patients were on atypical antipsychotic medication at the time of the experiment. Mean chlorpromazine equivalent (CPZ) dose was 325 mg/d (SD, 192). Clinical symptoms were assessed with the Brief Psychiatric Rating Scale (BPRS) (Overall and Gorham, 1962), the Scale for Assessment of Positive Symptom (SAPS) (Andreasen and Olsen, 1982), and the Scale for Assessment of Negative Symptom (SANS) (Andreasen and Olsen, 1982). Mean scores for BPRS, SAPS, and SANS were 22.5, 18, and 28.5, respectively (Table 1).

Control subjects were recruited. All subjects were paid for their participation. Their mean age was 35.5 years (SD, 7.2 years), and their mean education level was 14.3 years (SD, 1.9 years). Normal control subjects were screened to rule out schizotypal personality using the Schizotypal Personality Questionnaire (SPQ) (Raine, 1991) before the experiment. No control subject scored high on the SPQ; the mean score on the SPQ was 70.4 (SD, 56.1) for schizophrenia and 10.7 (SD, 6.2) for control subjects. Mean ages of control and schizophrenic subjects were 35.9 years (SD, 7.1 years) and 35.5 years (SD, 7.2 years), respectively. All patients were on atypical antipsychotic medication at the time of the experiment. Mean chlorpromazine equivalent (CPZ) dose was 325 mg/d (SD, 192). Clinical symptoms were assessed with the Brief Psychiatric Rating Scale (BPRS) (Overall and Gorham, 1962), the Scale for Assessment of Positive Symptom (SAPS) (Andreasen and Olsen, 1982), and the Scale for Assessment of Negative Symptom (SANS) (Andreasen and Olsen, 1982). Mean scores for BPRS, SAPS, and SANS were 22.5, 18, and 28.5, respectively (Table 1). Fourteen healthy control subjects (six females) with no history of mental illness or neurological disorders were recruited from the community. Their mean age was 35.5 years (SD, 7.2 years), and their mean education level was 14.3 years (SD, 1.9 years). Normal control subjects were screened to rule out schizotypal personality using the Schizotypal Personality Questionnaire (SPQ) (Raine, 1991) before the experiment. No control subject scored high on the SPQ; the mean score on the SPQ was 70.4 (SD, 56.1) of 72. No control subject was receiving psychotrophic medications. There was no significant difference between groups in age (t196 = 0.12; p = 0.90).

The experimental protocol was approved by the Institutional Review Board of Vanderbilt University. All subjects were given adequate information to insure that they understood the consent procedure before they were recruited. All subjects were paid for their participation.

**Psychophysical task.** Stimulus patterns were created in MatLab with the Psychophysics Toolbox (Brainard, 1997) and Video Toolbox (Pelli, 1997) and shown on a linearized video monitor (800 × 600 pixels resolution; 120 Hz). Viewing was binocular at 83 cm. The ambient illumination was 4.8 cd/m², and the background luminance was 60.5 cd/m².

The motion stimulus was a standard Gabor patch stimulus, a drifting vertical sine grating windowed by a stationary two-dimensional Gaussian envelope (Fig. 1). The size was defined as 2 SDs of the spatial Gaussian window. Stimulus duration was controlled by a temporal Gaussian envelope. This allowed brief presentations of moving stimuli. Duration was defined as 2 SDs of the temporal Gaussian. Subjects were instructed to foveate the fixation cross and initiate each trial by a key press. Then, after 600 ms, a drifting Gabor patch was presented foveally and subjects indicated the perceived direction (left vs right) by a key press. Positive feedback was provided. Spatial frequency was 1 cycle/° and speed was 4°/s (4 Hz). Three stimulus sizes (2r = 1, 2, and 4°) at two contrasts (2.8 and 42%) were investigated, yielding six conditions (Fig. 1). In the text, these three stimulus sizes are also referred to as small, medium, and large. The stimulus sizes were selected so that the average receptive field size in foveal MT falls somewhere between small and medium stimuli. Foveal receptive size estimates for macaque MT range from radius of 0.6° (Al-

### Table 1. The demographic data

<table>
<thead>
<tr>
<th></th>
<th>Control subjects (n = 14)</th>
<th>Schizophrenic subjects (n = 16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>35.5 (7.2)</td>
<td>35.9 (8.8)</td>
</tr>
<tr>
<td>Education (years)</td>
<td>14.3 (1.9)</td>
<td>12.9 (1.9)</td>
</tr>
<tr>
<td>Estimated full-scale IQa,b</td>
<td>100.3 (15.9)</td>
<td>100.4 (16.1)</td>
</tr>
<tr>
<td>BPRS</td>
<td>N/A</td>
<td>24.8 (16.1)</td>
</tr>
<tr>
<td>SANS</td>
<td>N/A</td>
<td>28.6 (18.8)</td>
</tr>
<tr>
<td>SAPS</td>
<td>N/A</td>
<td>25.1 (23.5)</td>
</tr>
<tr>
<td>SPQ</td>
<td>10.7 (6.2)</td>
<td>N/A</td>
</tr>
<tr>
<td>Global handedness scorec</td>
<td>70.4 (56.1)</td>
<td>59.1 (43.9)</td>
</tr>
<tr>
<td>CPZ equivalentd</td>
<td>N/A</td>
<td>325.0 (192.0)</td>
</tr>
<tr>
<td>Illness duration</td>
<td>N/A</td>
<td>13.4 (7.1)</td>
</tr>
<tr>
<td>Zygler scoree</td>
<td>6.0 (1.5)</td>
<td>2.6 (1.1)</td>
</tr>
</tbody>
</table>

Mean (SD) are shown. N/A, Not applicable.

aWechsler Adult Intelligence Scale, Revised (Wechsler, 1981).
bFor subject JY, the Barona Index (Spreen and Strauss, 1998) was used to compute estimated full-scale IQ because English was not this subject’s native language.
cGlobal Handedness Questionnaire (Ramol and Schachter, 1994).
dChlorpromazine dose equivalent (in milligrams).
eZygler Score of Social Functioning (Zigler and Levine, 1981).
bright and Desimone, 1987) to radius of 2.6° (Raiguel et al., 1995). As a comparison, V1 receptive fields tend to be ~10 times smaller than MT receptive fields at a similar eccentricity (Gattass and Gross, 1981; Albrecht and Desimone, 1987). Thus, our medium stimuli (2σ = 2°) are likely large enough to stimulate some surrounds in the foveal region of MT, and are more than an order of magnitude larger than V1 receptive fields. Moreover, our large moving stimuli (2σ = 4°) should stimulate surrounds of most foveal center-surround neurons in MT. Of course, this statement assumes that the properties of human and macaque MT are comparable (Rees et al., 2000) and that the receptive field sizes are similar for two species (Kastner et al., 2001).

Duration thresholds (82%) for perceiving stimulus motion (i.e., minimum stimulus duration required for 82% correct performance) were estimated in each block of trials by two interleaved QUEST staircases (Watson and Pelli, 1983). Based on a subject’s responses, the QUEST staircase method adaptively adjusts log_{10} of the stimulus duration. Accordingly, all analyses were performed on log_{10} duration thresholds.

Use of duration thresholds was based on the assumption that if the neural response to a stimulus is weak and/or noisy, then longer stimulus exposure will be required for correct perception. More specifically, deciding whether an object is moving in one of two possible directions can be conceptualized as a process involving accumulation of sensory evidence over time (Gold and Shadlen, 2000; Roitman and Shadlen, 2002). When neuronal responses are noisy or attenuated, as with a highly suppressed motion stimulus, sensory evidence accumulates more slowly and a correct decision thus will require longer exposure duration (Roitman and Shadlen, 2002).

Use of the staircase procedure ensured that both control subjects and schizophrenic patients performed at the same level of accuracy. Adjustment of task difficulty with an adaptive staircase such as the QUEST (especially with a conservative 82% threshold) minimizes the experience of failure, which presumably should have a positive effect on subjects’ motivation. For each condition, four blocks of trials were completed, with results of the first block discarded as practice. The order of conditions was randomized. The completion of the study required two 1 h sessions.

We were particularly interested in whether subjects’ performance improves or deteriorates with increasing stimulus size. Improving psychophysical thresholds with increasing size would indicate the presence of a mechanism that benefits from the integration of motion signals over space (i.e., spatial summation). In contrast, worsening performance with increasing size would indicate the presence of a mechanism that is negatively affected, or inhibited, by larger stimuli, a mechanism exhibiting spatial suppression.

Global form discrimination experiment
Subjects. A subset of the patients (n = 10; four females) also was tested on a global form task. The mean age of these patients was 38.3 years (SD, 7.8 years), mean education level was 12.6 years (SD, 2.02 years), and they had been ill for an average of 14.5 years (SD, 8.7 years).

Also tested on this form task were 15 healthy control subjects (9 females), recruited from the community, with no history of mental illness or neurological disorders. Their mean age was 36.6 years (SD, 11.8 years) and their mean education level was 13.5 years (SD, 2.3 years), values not significantly different from the patient group. Normal subjects were screened to rule out schizotypal personality using the SPQ (27) before the experiment. Mean score on the SPQ was 18.1 (SD, 11.1). No control subject was receiving psychotropic medications.

Psychophysical task. This four-alternative, forced-choice task measured the subject’s ability to group small, stationary line elements into a larger, global form. The entire screen of the computer monitor was divided into four equal-sized quadrants whose boundaries were delineated by thick black lines, and the screen was filled with short lines, most of which were oriented randomly. Each line subtended a visual angle ~30 min length by 2 min width, and the lines appeared black against a gray background. In one of the four quadrants, a small group of six lines formed a quasicircular shape within a randomly selected region of the quadrant, and the probability of appearance in any of the quadrants was equal over the trials. To manipulate the clarity of the target, we introduced “jitter” in the orientation of each line segment forming the quasicircular shape; jitter comprised an angular deviation among target contours from the canonical value specified by their positions on the circle. Therefore, larger degrees of jitter lessened the clarity of the target, resulting in impairment of subjects’ ability to identify the quadrant in which the target appeared. Displays remained visible until the subject responded. Viewing distance was 57 cm, and the visual angle of the target was ~2.5°. Examples of the displays are shown in the Figure 2.

Each subject was instructed to locate the quasicircular shape that looked like “stop sign” and to indicate in which quadrant it appeared. Although no sample stimuli were presented before the formal testing, the test began with a series of trivially easy trials (jitter, 0), so that each subject quickly became accustomed to the task. The degree of jitter over trials was adjusted by a staircase procedure to find the level of jitter at which the subject could identify the target location with >70% accuracy. Thus, the target became more difficult to detect after correct answers and less difficult after incorrect answers. Visual feedback showing correct location was provided after each trial. The total number of trials was 100, and the mean and SD of the jitter from the last 8 trials of the staircase were recorded as the estimate of the threshold. The subject could rest at any time during trials.

Results
When a moving stimulus was presented at low contrast, performance of both patients and controls improved as the stimulus...
indicates an abnormality in the perception of brief motions. In-
longer than duration thresholds measured for large moving stim-
ever, were presented for 300 ms, which is an order of magnitude
the motion of large, low contrast motions. Their stimuli, how-
(2003a) also reported that patients are unimpaired at perceiving
unimpaired in schizophrenia (Chen et al., 2003a). Chen et al.
can indicate either a deficit in perceiving low-contrast stimuli
motion perception. Uniform vertical shift of patients' thresholds
results suggests unimpaired spatial summation mechanisms in
motion perception. Uniform vertical shift of patients' thresholds
and/or a deficit in the perception of brief moving stimuli. Previ-
ous work has shown that contrast sensitivity for local motion is
unimpaired in schizophrenia (Chen et al., 2003a). Chen et al.
(2003a) also reported that patients are unimpaired at perceiving
the motion of large, low contrast motions. Their stimuli, how-
ever, were presented for 300 ms, which is an order of magnitude
longer than duration thresholds measured for large moving stim-
uli in our experiment, suggesting that the observed deficit likely
indicates an abnormality in the perception of brief motions. In-
deed, a deficit in processing of brief visual stimuli has been asso-
ciated with schizophrenia (Keri et al., 2005b).

At high contrast, performance of both patients and controls
deteriorated as the stimulus size increased \( F_{(2,27)} = 38; p < 0.001 \) (Fig. 3, right panel). This pattern of results can be con-
strued as an indicator of the presence of antagonistic center-
surround interactions (Tadin et al., 2003). At high contrast, no
main effects of group were found \( F_{(1,28)} = 1.76; p = 0.19 \). The only observed deficit was in a condition in which patients dis-
criminated a small (1°) high-contrast motion \( t_{(28)} = 2.29; p = 0.03 \). The magnitude of the observed deficit was comparable with the threshold increases observed for low-contrast moving stim-
uli (Fig. 3). Importantly, as the stimulus size increased, the
difference between patient and control data were eliminated. The
interaction, however, was not significant \( F_{(2,27)} = 1.72; p = 0.19 \). This pattern of results might indicate that patients are se-
lectively impaired in perceiving small moving objects. However,
we find no evidence for such selective impairment in the low-
contrast results. Another possibility is that the relatively smaller
threshold increase with increasing size reflects weaker center-
surround suppression in schizophrenia. Specifically, a deficit in
the perception of brief moving stimuli might be offset by weaker
center-surround suppression. Center-surround suppression im-
pairs motion perception only when the stimulus size is large,
greater than the small stimuli used in the present study (Tadin et
al., 2003). Thus, any "benefits" of reduced surround suppression
would be apparent only at larger stimulus sizes.

We also compared patients’ performance with low- and high-
contrast moving stimuli. The analysis revealed that those patients
who had lower thresholds for discriminating the motion of a
small, low-contrast stimulus also had low thresholds for discrim-
inating the motion of small, high-contrast stimuli \( r = 0.52; p = 0.04 \). This, perhaps expected, observation simply indicates that
patients who do better on one motion task tend do well in a
related motion task. In contrast, doing well when the stimulus
was a large, low-contrast stimulus does not predict patients’ per-
formance with large, high-contrast moving stimuli \( r = 0.016; p = 0.95 \). Control subjects showed a very similar pattern of
results. This observation suggests that factors in addition to the
general ability to perceive motion determine motion sensitivity
for large, high-contrast stimuli. One such factor is the strength of
surround suppression.

To quantify the strength of center-surround suppression at high
contrast, we computed the "suppression index": \( \log_{10}(\text{threshold for the large, high-contrast stimulus}) - \log_{10}(\text{threshold for the small, high-contrast stimulus}) \). Analogously, to quantify the strength of spatial summation at low contrast, we computed the "summa-
tion index": \( \log_{10}(\text{threshold for the large, low-contrast stimulus}) - \log_{10}(\text{threshold for the small, low-contrast stimulus}) \). The sup-
pression index is typically positive, because thresholds for large,
high-contrast stimuli tend to be high relative to thresholds for
small, low-contrast stimuli. In contrast, the summation index is
typically negative, because thresholds for large, low-contrast
stimuli tend to be low relative to thresholds for small, low-
contrast stimuli. Next, we compared suppression and summation
index estimates with patient scores on scales used to assess
clinical symptoms in schizophrenia: BPRS, SANS, and SAPS (Fig.
4). The summation index showed no dependency on symptom
severity (all \( r < 0.36; \) all \( p > 0.17 \)). The suppression index was
not correlated with either BPRS \( r = -0.32; p = 0.22 \) or SAPS
\( r = 0.1; p = 0.71 \), but it was correlated with negative symptom
severity (SANS) \( r = -0.54; p = 0.03 \). Thus, patients with more
severe negative symptoms exhibited weaker center-surround
suppression. Moreover, from Figure 4, it is apparent that most
patients (13 of 16) demonstrated center-surround suppression
that was weaker than the average suppression measured for con-
control subjects; and 10 of 16 patients had suppression indices lower
than the lower quartile of the control data.

**Median split results**

**High contrast**

To further examine the relationship between symptom severity and high- and low-contrast results, we split patients into two
groups relative to the median score on BPRS, SANS, and SAPS
(Fig. 5A). At high contrast, we found an interaction when patients
were split according to BPRS scores \( F_{(4,52)} = 2.97; p = 0.028 \),
and there was a trend toward interaction when patients were split
according to SANS scores \( F_{(4,52)} = 2.40; p = 0.06 \). No main
effects of group were found (all \( F_{(2,27)} < 2.34; \) all \( p > 0.12 \)).
Patients with high BPRS and SANS scores tend to have higher
thresholds for small and medium moving stimuli and slightly
lower thresholds for the largest stimulus tested (the results for
patients with low BPRS and SANS scores were essentially identi-
cal to control results). This tendency is also found when BPRS
and SANS scores are correlated with duration thresholds (Fig. 5A,
numbers under data symbols): positive correlations are found for
small- and medium-size stimuli, and slight negative correlations
were observed for large moving stimuli.

We performed an analogous three-group analysis on suppres-
Significant effects were found when patients were split according to BPRS ($F_{(2,27)} = 5.29; p = 0.012$) and SANS scores ($F_{(2,27)} = 4.57; p = 0.02$). No effect was found when patients were split according to SAPS scores ($F_{(2,27)} = 1.09; p = 0.35$). This pattern of results indicates that patients with high BPRS and SANS scores exhibit weaker center-surround suppression than controls and patients with milder symptoms.

Finally, 4 of 16 patients exhibited no surround suppression: increasing stimulus size at high contrast had no effect on their thresholds (on average, their thresholds increased by $<2$ ms).

Similar to other patients, this subgroup had elevated duration thresholds when the moving stimulus was small (13 ms threshold increase; $t_{(16)} = 3.48; p = 0.003$). However, when the stimulus was large, patients in this subgroup exhibited thresholds 30%
lower than control subjects’ thresholds (9 ms threshold decrease; \( t_{(16)} = 2.25; p = 0.039 \)). This indicates that a lack of center-surround suppression can result in reduced thresholds for perceiving large, high-contrast motion. Moreover, this threshold reduction can reach levels where patients are actually outperforming control subjects. We examined clinical profiles of these four patients, but we found no significant difference from the rest of the schizophrenic subjects. The small number of patients with no surround suppression, however, limits our ability to discern small but real differences between two groups.

**Low contrast**

At low contrast (Fig. 5A), schizophrenic psychosis was associated with higher duration thresholds (all group \( F_{(2,27)} > 3.58; \) all \( p < 0.04 \)). A trend toward significant interaction was found when patients were split according to SANS scores (\( F_{(4,52)} = 2.40; p = 0.06 \)). However, an analogous three-group analysis on summation indices (Fig. 5B, dark bars) yielded no differences between groups (all \( F_{(2,27)} < 1.35; \) all \( p > 0.28 \)). Thus, the overall pattern of results was similar across different groups except for vertical shifts indicated by significant group differences. To further examine the differences between patients with severe and mild symptoms, we excluded control subjects from the analysis of duration thresholds. The effect of group was significant when patients were split according to SANS scores (\( F_{(1,14)} = 4.6; p = 0.05 \), and failed to reach significance when patients were split according to BPRS and SAPS scores (all \( F_{(1,14)} < 2.24; \) all \( p > 0.15 \)).

Overall, both the correlation and the median split analyses revealed an inverse relationship between severity of negative symptoms in schizophrenia and the strength of center-surround suppression at high contrast. Center-surround suppression in control subjects was over 2.5 times stronger than center-surround suppression estimated for patients with severe negative symptoms (Fig. 5B).

**Medication**

It is important to consider possible effects of medication. For example, there is evidence suggesting that dopamine antagonists affect visual contrast sensitivity (Chen et al., 2003b). Dopamine is critical for the ability to detect visual contrast, and antipsychotic drugs block dopamine receptors. The newer, “atypical” antipsychotics, such as risperidone or olanzapine, block dopamine receptors for much shorter periods than typical neuroleptic drugs such as haloperidol. Indeed, Chen et al. (2003b) found that the thresholds for detecting visual contrast in schizophrenia patients taking typical antipsychotic drugs were elevated. In contrast, the thresholds for those who were taking atypical antipsychotics were the same as that found in healthy subjects. All of our patients were receiving atypical antipsychotic drugs; thus, we did not expect to find perceptual deficits associated with typical antipsychotics.

Indeed, we found no correlation between CPZ dose and suppression and summation indices (all \( r < 0.32; \) all \( p > 0.23 \)). We also examined whether medication dose for four patients that exhibited no surround suppression differed from the rest of schizophrenic patients, but we did not find any differences (\( t_{(14)} = 0.15; p = 0.88 \)). Moreover, patients’ thresholds on different motion tasks did not correlate with the CPZ dose. Highest correlation was found between CPZ and thresholds for the big, high-contrast stimuli (\( r = -0.46; p = 0.08 \)). All other correlations were \(<0.20 \). Finally, there was no relationship between CPZ dose and symptom severity as assessed by BPRS, SANS, and SAPS (all \( r < 0.40; \) all \( p > 0.13 \)).

It has been hypothesized that weakened surround suppression might be caused by an abnormal GABAergic system (Betts et al., 2005). Indeed, GABAergic effects on visual perception (Blin et al., 1993) and motion integration and segmentation (Giersch and Lorenceau, 1999) have been reported. Thus, use of medication that has considerable effects on the GABAergic system might lead to unwanted confounds. However, atypical antipsychotic drugs that our patients were taking mostly work on dopamine receptors and, to a lesser degree, on serotonergic receptors. Thus, any effects on the GABAergic system are indirect and likely minor.

**Global form discrimination experiment**

The results presented so far demonstrate a motion-processing deficit in schizophrenia. It is, however, useful to examine performance of schizophrenic patients in a nonmotion visual task. An unimpaired performance on another visual task would suggest that these patients do not exhibit a general visual perception deficit. Moreover, psychophysical experiments are relatively tedious and sustaining motivation over the course of an experiment can be difficult. Thus, it is important to establish that patients can perform within the normal range in a comparable psychophysical task.

To perform these necessary controls, we measured patients’ perceptual ability to group small, stationary line elements into a larger, global form (Fig. 2). The mean jitter threshold values (the range of angular deviations among line elements) for patients did not differ from control data (\( t_{(23)} = 0.807; p = 0.43 \)). This result essentially replicates a previous finding from our laboratory (Kim et al., 2005) and demonstrates that schizophrenic patients can perform in a normal range on a nonmotion perceptual task. Performance of patients on the global form task did not correlate with overall, positive, nor negative symptoms. These results provide additional evidence that visual processing in schizophrenia is relatively intact in visual tasks requiring processing of detailed form information (O’Donnell et al., 1996, 2002).

**Discussion**

We show that schizophrenic patients have elevated direction discrimination thresholds while performing normally in a shape discrimination task. This result provides additional evidence for the existence of a motion processing deficit in schizophrenia (Stuve et al., 1997; Chen et al., 1999a,b,c, 2003a, 2004, 2005; Li, 2002; Slaghuis et al., 2005; Kim et al., 2006). More importantly, at high contrast, schizophrenic patients exhibit reduced center-surround suppression. Because of this reduction in estimated surround suppression, the average thresholds of schizophrenic subjects for the largest stimulus size were the same as those for the controls (Fig. 3). In fact, four patients showed no effect of stimulus size at high contrast, a finding that we have yet to observe in normal, age-matched subjects. Those patients also had lower thresholds (better performance) than control subjects for perceiving large high-contrast moving stimuli. This counterintuitive observation is likely caused by weakened suppressive mechanisms in motion processing, mechanisms that normally yield elevated thresholds for perceiving large, high-contrast motion in healthy young subjects.

At low contrast, changes in stimulus size have essentially the same effect for schizophrenic and control subjects. Thus, the main qualitative difference between schizophrenic patients and control subjects is found at high contrast, where increases in the stimulus size had a much larger effect in motion perception of control subjects. In other words, the low contrast condition can
also be considered a control condition for the general effect of stimulus size.

Possible functional consequences of weakened surround suppression

Lesser impairment in motion discrimination with increasing stimulus size observed in schizophrenia, however, should not be considered a perceptual advantage, because it indicates weaker surround suppression. Suppressive center-surround interactions have been implicated in a variety of perceptual functions (Tadin and Lappin, 2005). In motion perception, center-surround interactions have been linked with the segmentation of moving objects from the background (Nakayama and Loomis, 1974; Allman et al., 1985; Born et al., 2000), slow visual pursuit of moving objects (Born et al., 2000) and perception of their three-dimensional shape (Xiao et al., 1995; Buracas and Albright, 1996). Abnormality in surround suppression may impair these important perceptual functions. Indeed, schizophrenic patients have trouble segmenting moving forms from the background (Schwartz et al., 1999; Kim et al., 2005).

Comparison with other contextual processing deficits

Center-surround interactions are a type of contextual modulation in which visual stimulation of the surround modulates the response in the center region. Our report of abnormal center-surround interactions in motion perception is consistent with other studies reporting abnormal contextual interactions in schizophrenia (Must et al., 2004; Dakin et al., 2005; Keri et al., 2005a,b). In some cases, contextual interactions can affect the appearance of visual stimuli (e.g., contrast) (Chubb et al., 1989), implying that, in those cases, abnormally weak contextual modulations might counterintuitively yield a veridical perception of the affected stimulus property. Indeed, schizophrenic patients are more accurate at perceiving stimulus contrast under contextual manipulations that typically affect contrast perception of control subjects (Dakin et al., 2005). Moreover, Keri and colleagues found that weakening of contextual interactions in schizophrenia was correlated with negative symptom severity in one study (Keri et al., 2005b), but not in two related investigations (Must et al., 2004; Keri et al., 2005a). Testing of high-functioning patients (mean SANS, <10), however, likely reduced the chances of finding a significant correlation.

Potential causes of abnormal center-surround interactions in schizophrenia

Psychophysically observed center-surround interactions in motion perception have been linked with center-surround antagonism in cortical area MT (Tadin et al., 2003). Specifically, the dependency of psychophysical surround suppression on contrast, eccentricity, stimulus isoluminance, and motion adaptation is consistent with what is known about response properties of neurons in MT. Moreover, our medium and large stimuli are, respectively, large enough to partially and substantially stimulate the surrounds of foveal MT receptive fields (for details, see Materials and Methods). Thus, abnormally weak surround suppression in schizophrenia suggests the existence of a deficit in MT processing. Other research has shown that schizophrenic patients are deficient in perceiving random-dot motion (Chen et al., 2003a), which is a task that is also linked with MT neurons (Salzman et al., 1990). Likewise, an impairment of the later stages of motion processing is suggested by the observation that velocity discrimination deficits in schizophrenia are independent of contrast (Chen at al., 2004). Furthermore, a recent functional mag-
negative symptoms in medicated (Wolkin et al., 1992; Lahti et al., 2001) and neuROLEPTIC-naive (Andreasen et al., 1997) patients. Thus, weakened frontal cortical control over cortical and subcortical circuits seems to lie at the heart of negative symptomatology. In other words, disinhibition (i.e., disinhibited dopamine sys-

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As outlined in Introduction, a large number of visual defects in schizophrenia tend to involve perception and visual pursuit of dynamic and moving stimuli. Many of these processes have been linked with the magnocellular visual processing stream, and as-

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