Disorders of Agency in Schizophrenia Correlate with an Inability to Compensate for the Sensory Consequences of Actions

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Summary

Psychopathological symptoms in schizophrenia patients suggest that the concept of self might be disturbed in these individuals [1]. Delusions of influence make them feel that someone else is guiding their actions, and certain kinds of their hallucinations seem to be misinterpretations of their own inner voice as an external voice, the common denominator being that self-produced information is perceived as if coming from outside. If this interpretation were correct, we might expect that schizophrenia patients might also attribute the sensory consequences of their own eye movements to the environment rather than to themselves, challenging the percept of a stable world. Indeed, this seems to be the case because we found a clear correlation between the strength of delusions of influence and the ability of schizophrenia patients to cancel out such self-induced retinal information in motion perception. This correlation reflects direct experimental evidence supporting the view that delusions of influence in schizophrenia might be due to a specific deficit in the perceptual compensation of the sensory consequences of one's own actions [1–6].

Results

Auditory hallucinations, thought insertions, and delusions of influence have been declared first-rank symptoms and hallmarks of psychopathology in schizophrenia patients [7]. They belong to the cluster of positive symptoms in schizophrenia, and this cluster demonstrates a high interindividual and crosscultural stability

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and a high positive predictive value for the disorder [8]. In the presence of many of these positive symptoms, internally generated cognitive phenomena are being misattributed to the external world, suggesting an impaired ability to ascribe agency to self-produced events. However, despite recent progress in clarifying the pathophysiological mechanisms of the disorder, the functional bases of disorders of agency have remained elusive. During the last decades, theoretical groundwork was laid for a further understanding of the mechanisms that contribute to the perceptual distinction between sensory events that occur as a result of one's own actions and events that occur as the result of someone else's actions [9]. Following these ideas, Frith proposed a cognitive model of self-agency [1, 2], here referred to as the "comparator model" (Figure 1A), which tries to explain delusions of influence in schizophrenia. According to this model, the sensory consequences of a given motor command are predicted ("predicted state"). By comparing this predicted state with the actual sensory afference ("actual state"), we are able to attribute self-agency to sensory events: If both signals match, we are the authors of the sensory information. If they do not match, the difference is attributed to the environment. Such a comparator mechanism might represent a specific faculty of the self, one that is disturbed in certain schizophrenia patients [1–3]. In fact, patients suffering from hallucinations and/or delusions of influence have difficulties in the distinction of self-produced and externally produced actions [4–6].

In order to investigate the mechanisms underlying these disorders of agency, we investigated the ability of schizophrenia patients to discriminate between retinal image motion resulting either from their own smooth-pursuit eye movements or from external motion sources. While such smooth pursuit is performed, the images of a stationary environment inevitably slip over the retina with a velocity equivalent to that of the eye rotation. If we relied on retinal information only, we would misattribute the image motion to the environment rather than to ourselves and thus misperceive the world as moving. This interpretation is avoided by comparing the actual image slip with the amount of image motion predicted on the basis of the eye-movement motor command. If both signals match, the retinal image slip is interpreted as being self produced, whereas if they do not match, the difference must be attributed to the external world [9, 10]. Thus, within the framework of motion perception, self-agency is explained by the same comparator mechanism (Figure 1A). Accordingly, the amount of residual (misattributed) background motion perceived during smooth pursuit across a stationary environment is a highly specific behavioral probe to validate putative deficits in the comparator mechanism in schizophrenia patients; a greater amount of residual motion should be perceived by subjects suffering from delusions of influence. This is, as shown here, indeed the case.

In 14 schizophrenia patients and 14 healthy control subjects, we estimated the amount of external background motion that had to be added in order to com-
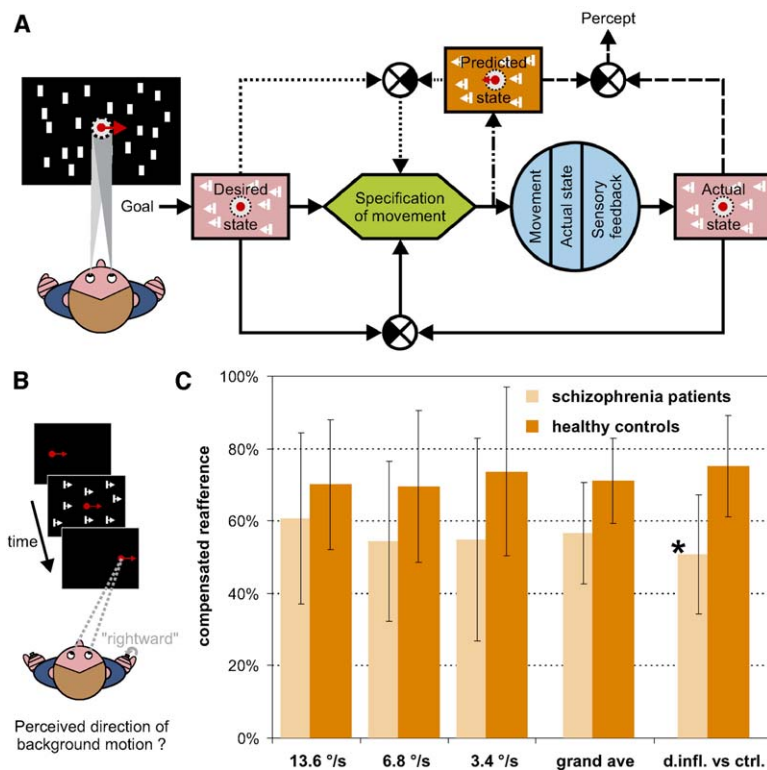
Figure 1. Perceptual Cancellation of Self-Induced Sensory Information

(A) The figure shows the comparator model [1, 2]. According to this model, the motor system can be considered a control system with the input being a "desired state" and the output being the "actual state estimate." On the basis of these two representations, the system specifies a sequence of motor commands in order to reach a certain goal. For example, during smooth pursuit of a moving target (see left sketch), subjects try to stabilize the retinal image of the moving object on the fovea to improve vision (desired state). To achieve this goal, appropriate motor commands have to be generated. This process depends on feedback control. By comparison of the desired and the actually estimated state, a motor error, which is fed back to the system to improve its functioning (solid lines), can be calculated. Moreover, the system makes predictions on the outcome of our behavior on the basis of a given motor command ("predicted state"). Such predictions can be used for feed-forward control (central monitoring) of the movement (dotted lines) but also to remove sensory feedback that is self produced (dashed lines). By the latter comparison, self-agency can be attributed to sensory events: If the predicted state matches the estimated actual state, the afferent information is self-produced, whereas if these signals do not match, the difference must be attributed to the environment. Accordingly, we perceive a pursued object as moving while the world (random-dot background) appears to be stationary.

(B) By varying the speed of a structured background during horizontal smooth pursuit, we determined the amount of image motion necessary to render this background perceptually stationary (50% rightward and 50% leftward answers). The larger the deviation of this point of subjective stationarity from the optimum of 0°/s, the less precise the compensation of the self-induced background-image motion, namely the compensated reafference (CR).

(C) The amount of compensated reafference (CR) is plotted as a function of target velocity and separately for the groups of schizophrenia patients and healthy controls. In addition, we show the grand average for both groups as well as a comparison of the subgroup of patients suffering from delusions of influence versus their matched controls. Error bars indicate 95% confidence intervals.

pensate the percept of residual background motion, rendering the background stationary (compare Figure 1B). In other words, at this point of subjective stationarity (PSS), the amount of external velocity of the background equals the amount of motion perceived during pursuit across a stationary background. Having determined the background velocity at the PSS, we could calculate the fraction of self-induced retinal image slip, compensated for by the sensory predictor. The size of this "compensated reafference" (CR) is given by equation (1):

$$CR = [V_{reafference} - V_{extern}] / V_{reafference} \quad (1)$$

V_{extern} represents the external velocity (V) of the background at the PSS, whereas $V_{reafference}$ reflects the full amount of self-induced image motion and is given by the velocity of the smooth-pursuit eye movement. According to equation (1), the closer V_{extern} at the PSS is to the optimal value of 0°/sec (stationarity), the better the compensation (CR approaching 100%). On the other hand, if the PSS equals eye velocity, (i.e., $V_{extern} = V_{reafference}$), there is no compensation at all (CR = 0%). Note that this measure is independent of the actual eye velocity and therefore can be compared for different target velocities irrespectively of possible differences in

smooth-pursuit performance between controls and the patient group.

We measured the CR for each individual subject in the two groups for three different target velocities (3.4°/s, 6.8°/s, and 13.6°/s). The mean values of each group are depicted in Figure 1C. As is obvious from this figure, CR values of both groups, patients (57%, grand average) and controls (71%), were significantly smaller than the optimum of 100%. This poor performance in healthy subjects might be surprising at first glance. However, this result simply reflects the fact that the ability to compensate for the retinal consequences of smooth pursuit under laboratory conditions is sufficient only if the conditions mimic those prevailing in a natural environment. For instance, backgrounds that are considerably smaller than a full visual field and are, moreover, presented only shortly, as in our experiment, are known to result in a nonoptimal compensation of self-induced image slip [e.g., 11]. More important than the absolute size of compensation for the configuration given is the question of whether there might be differences in performance between healthy controls and schizophrenia patients. Although there was a tendency for the patients to compensate less than the controls, this difference (14%) did not reach significance for any

of the target velocities used (two-way ANOVA with the factors "group" [$F_{(1, 78)} = 2.29$, n.s.] and "target velocity" [$F_{(2, 78)} = 0.04$, n.s.] and their "interaction" [$F_{(2, 78)} = 0.08$, n.s.]).

One might argue that the lack of a consistent difference between groups might have been due to the patients' deviating from the normal CR in individually varying directions, balancing out on the group level. This does not seem to be the case, as shown by an analysis of a "CR deviation" measure, given by the root-mean-squares of the individual CR differences from the CR average of healthy subjects and calculated for each subject and each target velocity separately. Thus, *the smaller* this standardized measure of absolute deviation, *the more accurate* the compensation of self-induced image motion with respect to reference values obtained in normal controls. CR deviation, averaged across the three velocities tested, amounted to 36% (grand average) in schizophrenia patients and 32% in healthy controls. This small difference between groups did not reach statistical significance (two-way ANOVA with the factors "group" [$F_{(1, 78)} = 0.32$, n.s.] and "target velocity" [$F_{(2, 78)} = 0.82$, n.s.] and their "interaction" [$F_{(2, 78)} = 0.58$, n.s.]). Furthermore, putative differences in the CR or CR deviation were not veiled by abnormalities in smooth-pursuit eye movements, coherent ("global")-motion perception, or increased response variability, which have been regularly reported for schizophrenia patients [e.g., 12–14] (for further details please see Figure S1 in the Supplemental Data available with this article online).

In summary, this first line of comparison of patients and healthy controls failed to reveal any indication of a malfunctioning of the comparator mechanism in schizophrenia patients. However, according to the line of arguments put forward in the introduction, one should expect such deficits only in those schizophrenia patients suffering from disorders of agency. In fact, when we only compared the CR measure for a subgroup of patients showing delusions of influence (51%, grand average, n = 11) with the CR values of their matched controls (75%, compare Figure 1C), these patients were significantly impaired in their ability to compensate for the amount of self-induced image motion during smooth pursuit (two-way ANOVA with the factors "group" [$F_{(1, 60)} = 4.63$, $p < 0.05$] and "target velocity" [$F_{(2, 60)} = 0.06$, n.s.] and their "interaction" [$F_{(2, 60)} = 0.01$, n.s.]). This deficit appears specific because it was not accompanied by any impairment in smooth pursuit (two-way ANOVA with the factors "group" [$F_{(1, 60)} = 0.00$, n.s.] and "target velocity" [$F_{(2, 60)} = 361.35$, $p < 0.001$] and their "interaction" [$F_{(2, 60)} = 0.17$, n.s.]) or coherent-motion perception in this subgroup of patients (t test [$t_{(26)} = 1.80$, n.s.]).

In order to test this finding more rigorously, we performed a regression analysis within the group of schizophrenia patients as a whole. Such a within-group analysis has the advantage that nonspecific effects caused by medication, effects that differed only minimally between patients, can be ruled out. Thus, we correlated specific aspects of our patients' psychopathology as assessed by the Scale for Assessment of Positive Symptoms (SAPS, see Experimental Procedures) with our four task-specific perceptual and behavioral measures: (a) CR; (b) CR deviation; (c) smooth-pursuit eye velocity; and (d) detection thresholds for coherent-motion perception. Out of the regressions calculated (n = 4), the only one that turned out to be significant was the one between the SAPS and the measure of CR deviation (b: $R^2 = 0.52$; $p < 0.01$, corrected for multiple comparisons. a: $R^2 = 0.06$. c: $R^2 = 0.07$. d: $R^2 = 0.01$, n.s.): The larger the score for the assessment of positive symptoms, the less accurate the perceptual compensation of self-induced retinal image motion of the world. In the next step, we asked whether any specific class of symptoms assessed by the SAPS might be predominantly related with a reduced ability to cancel out smooth-pursuit-induced sensory information. To this end, we performed an additional statistical analysis in which we used several items of the SAPS as further regressors: (I) hallucinations; (II) delusions; (III) residual positive symptoms; (II-a) delusions of influence; and (II-b) residual delusions. Each of these subscores was again correlated with the four behavioral measures (a–d; n = 20 regressions). As shown in Figure 2A, CR deviation was correlated with score II (i.e., delusions [$R^2 = 0.59$; $p < 0.05$, corrected for multiple comparisons; also see Figure 2B]) rather than with hallucinations (score I: $R^2 = 0.25$; n.s.) or other positive symptoms (score III: $R^2 = 0.01$; n.s.). Score II considered different types of delusions, which are reflected by subscores II-a and II-b. Out of these, only the one describing delusions of influence (subscore II-a) showed a significant correlation with CR deviation, too ($R^2 = 50$; $p < 0.05$, corrected for multiple comparisons; see Figure 2A). In other words, the correlation between the SAPS and CR deviation was mainly accounted for by the contribution of delusions (score II)—more specifically, delusions of influence (subscore II-a). Besides, none of the remaining behavioral parameters (i.e., the compensated reafference, smooth-pursuit velocity, or coherent-motion perception), did correlate with any of the symptoms assessed in the group of schizophrenia patients in this second line of analyses.

Discussion

This study tried to shed light on the mechanisms underlying disorders of agency in schizophrenia patients. It was guided by the idea that such patients might have problems representing the predicted sensory consequences of their own actions and that they might therefore misattribute sensory events as arising from the environment rather than from themselves [1–3]. The perception of visual motion during pursuit eye movements is a task that is highly dependent on faithful information on the visual consequences of the eye movements and thus offers a simple model to gauge the availability of reliable sensory predictions in schizophrenia patients [9, 10]. Although the group of schizophrenia patients as a whole did not deviate from the group of healthy controls in any of the perceptual and behavioral measures considered, those patients suffering from delusions of influence were more impaired in predicting the visual consequences of their eye movements the more they suffered from this kind of self-disturbance.
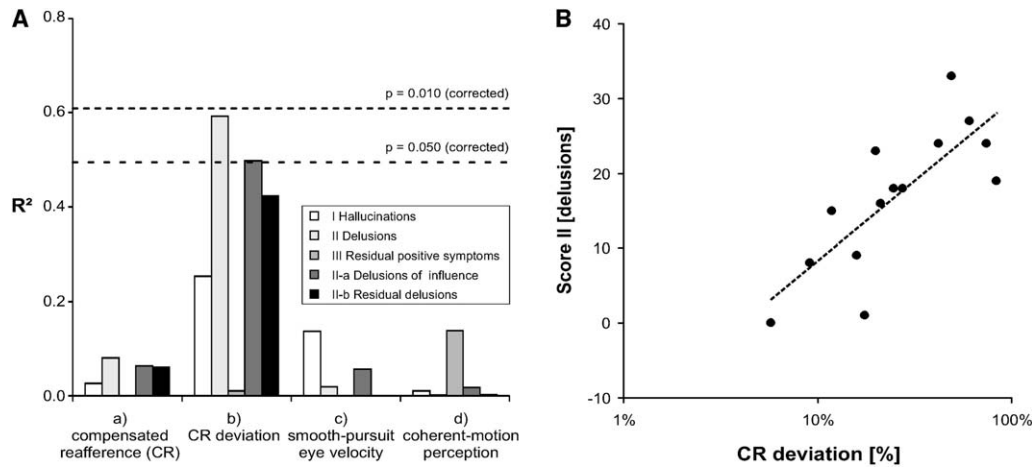
Figure 2. Correlation of Positive Symptoms with Behavioral Parameters

(A) Summary of all correlation coefficients (R^2) obtained in a multiple-correlation analysis between different scores for the assessment of positive symptoms (for details, see Experimental Procedures) and several behavioral measures (as described in detail in Results). The corresponding p values are indicated by the horizontal lines. P values were adjusted for multiple comparisons according to the Bonferroni procedure.

(B) Delusions (score II, SAPS) plotted as a function of the deviation of the compensated reafference (CR). Note that the two factors exhibit a highly significant correlation (compare with [A]).

A possible concern could be that the close relationship between delusions of influence and impaired perceptual compensation of smooth-pursuit-induced image motion, as described here, might actually be the consequence of common dependencies of both on a third functionality. Specifically, both might be independent expressions of a more global cognitive dysfunction. On the other hand, in view of the frequent accounts of disturbed-pursuit eye movements [e.g., 12] and deficits in visual-motion processing [e.g., 13, 14] in schizophrenia patients, the impaired perceptual compensation during pursuit might be secondary to disturbances of these more elementary functional modules. We think that these concerns can be dispelled. First, it has been shown convincingly that self-monitoring deficits in schizophrenia patients are not correlated with widespread, general disturbances of cognitive functions [15, 16]. Second, the amount of delusions did not show any significant dependency on smooth-pursuit gain or the visual perception of coherent motion in the absence of eye movements in our study. The lack of such correlations most likely reflects the individual psychopathology of our patients, who predominantly exhibit positive symptoms: There seems to be no interrelation between these symptoms and the initiation and maintenance of smooth-pursuit eye movements [17] and thus the underlying processing of visual motion [18]. This does not invalidate the idea that pursuit disturbances [e.g., 12] as well as deficits in visual-motion perception [13, 14] are more frequent in the population of schizophrenia patients as a whole. However, it rules out the possibility that the perceptual-compensation deficit observed by us could be secondary to such problems.

Several studies have reported disorders of agency in schizophrenia via self-attribution tasks similar to the one described here; the experimental strategy was usu-ally based on movements (and their sensory consequences) that were fed back visually to the subjects with well-defined distortions. The question was whether subjects were able to detect these distortions and how accurate self-attribution judgments were made. Visual feedback on the action (hand and finger movements, reaching, drawing, etc.) was manipulated in the spatial and the temporal domain [5, 6, 19–21]. Thus, rather than estimating sensory predictions or the outcome of their comparison with the actual afferent signal—as it was done here—all of these previous studies measured detection thresholds: Schizophrenia patients always had problems in recognizing feedback manipulations and tended to attribute what they saw to their own agency, even if sensory feedback information was clearly different from the action they performed. This behavior, which was termed "hyperassociation" or "overattribution," cannot be explained by the comparator mechanism—if patients are not able to form representations of the predicted sensory consequences of their actions, they should misattribute self-produced sensory information to external sources rather than exhibit hyperassociations. However, such overattribution might simply reflect the indispensability of the comparator mechanism: Subtle distortions of visual feedback on self-movements, as applied in the aforementioned studies [5, 6, 19–21], are no longer likely to be detected if the comparison with a precise [22] and continuously optimized [10] internal prediction on the outcome of our behavior is lacking. As a consequence, the use of external information for self-ascriptions (for instance, vision [23]) gains more importance. On the one hand, this might lead to hyperassociations if external cues are manipulated experimentally. On the other hand, an episodic misattribution of self-produced sensory information to external sources might result whenever such external cues are not available—one of the major hall-

marks of schizophrenic psychopathology. Thus, hyper-associations seem to be compatible with the comparator model. However, as already mentioned above, they do not reflect compelling evidence for its implementation. In contrast, the behavioral probe used in the present study directly reflected the output of the comparison between predicted and actually estimated sensory feedback (Figure 1A), indicating a specific impairment in patients suffering from delusions of influence: These patients might not be able to form an appropriate prediction on the outcome of their behavior, a major key to the ascription of self-agency to sensory events.

Experimental Procedures

Subjects

A group of 14 schizophrenia patients participated in this study (7 men, 7 women, average age = 29), and two groups of age-matched healthy control subjects (as specified below) participated in this study. All subjects had normal or corrected-to-normal visual acuity and gave their written informed consent according to the declaration of Helsinki. Schizophrenia patients were recruited from the Psychiatric University Hospital in Tübingen, Germany. All patients met the DSM-IV criteria for schizophrenia. Furthermore, all of them met the criteria for the paranoid subtype of the disorder with predominant delusions and hallucinations. Negative symptoms were only moderately present in our patients. All of them were medicated with atypical neuroleptics. Hallucinations and delusions were quantified by the Scale for Assessment of Positive Symptoms (SAPS) [24]. The mean SAPS was 30.2 ± 8.8 (95% confidence interval). The following subscores were assessed: score I hallucinations, 8.8 ± 4.5 (average ± 95% confidence interval); score II delusions: 16.8 ± 5; score III residual positive symptoms [i.e., SAPS minus (score I + II)], 4.6 ± 1.9; score II-a delusions of influence, 6.1 ± 2.8; score II-b residual delusions (i.e., score II minus score II-a), 9.9 ± 3.2.

Experimental Design

All psychophysical tests followed an adaptive staircase procedure (PEST) [25], forcing subjects to select one of two alternative responses in an individual trial. Thresholds, as defined below, were determined by means of a probit analysis [26]. Stimuli were back projected on a translucent screen (frame rate 60 Hz, 1280 × 1024 pixels) in a dark experimental room. Viewing distance was 148 cm. During all tests, eye movements were monitored with an infrared-video eyetracker. Recordings were stored and analyzed online at a sampling rate of 50 Hz by a workstation that also controlled the presentation of the stimuli. When deviations of eye position from the position of the given fixation target exceeded a certain predefined amount (see below), they were fed back acoustically as errors, and the corresponding trials were discarded. Eye movements were analyzed according to procedures described in detail elsewhere [10].

In the first experiment, we measured the amount of residual image motion perceived during smooth-pursuit eye movements across a stationary structured background. Pursuit was elicited by a red dot (diameter 15 min of arc), which moved from left to the right at a constant velocity of either 3.4°/s, 6.8°/s, or 13.6°/s spanning a visual angle of 5°, 10°, or 20°, respectively. Trials in which eye position deviated by more than 1°, 2°, or 4° from the fixation target, respectively, were detected online and discarded from further analysis. The percentage of such "invalid" trials did not differ between groups or for different target velocities (two-way ANOVA with the factors "group" [$F_{(1, 78)} = 0.49$, n.s.] and "target velocity" [$F_{(2, 78)} = 2.08$, n.s.] and their "interaction" [$F_{(2, 78)} = 1.70$, n.s.]). Different target velocities were presented in separate blocks. The order of these blocks was randomly selected for each subject. Temporally located in the middle of the target sweep, a background pattern was presented for 200 ms. This background stimulus subtended 42° × 38° of visual angle and consisted of 230 white dots (diameter 15 min of arc, 3.6 cd/m^2) on an otherwise dark background (0.0 cd/m^2). Subjects were asked to report the direction of perceived background motion, which was varied by the staircase procedure in order to estimate the point of perceived stationarity (PSS) of the background. The PSS was defined as the background velocity giving on average 50% leftward and 50% rightward responses. The velocity of the background at the PSS is a direct estimate for the ability to compensate self-induced image motion, namely the compensated reafference (CR; see equation 1 in Results). Because there was no interaction between CR values of the schizophrenia patients and target velocity, these measures were pooled for the correlation with the individual clinical scores. Overall, ten men and four women (average age 27) served as healthy control subjects.

In a second experiment, we tested for the ability to detect coherent motion in a random-dot display. Subjects were confronted with two rectangular apertures (18° × 18° each), centered at 2.5° right and left of the fixation point. Each aperture contained 100 dots (diameter 15 min of arc, 3.6 cd/m^2) moving at 6°/s and whose lifetime was unlimited. Presentation time was 200 ms. Whereas all dots in one of the apertures moved in random directions, a fraction of the dots in the other aperture moved coherently in a common direction, chosen randomly between 0° and 360°. The choice of the aperture containing coherent motion and the percentage of coherently moving dots in that aperture changed from trial to trial, the latter as determined by the PEST-staircase procedure. On each trial, subjects were required to indicate, while maintaining fixation of the central cue, the aperture containing coherently moving dots. Eye position was controlled online as described earlier, and the trial was discarded if the eyes left a position window of 4° centered on the fixation cue. The motion-detection threshold was defined as the "coherency level" at which subjects responded correctly in 75% of the time. Ten men and four women (average age 29) served as healthy control subjects.

Supplemental Data

One supplemental figure can be found in the Supplemental Data available with this article online at http://www.current-biology.com/cgi/content/full/15/12/1119/DC1/.

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