

Association Between Failures in Perceptual Updating and the Severity of Psychosis in Schizophrenia

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 Supplemental content

IMPORTANCE Recent accounts suggest that delusions and hallucinations may result from alterations in how prior knowledge is integrated with new information, but experimental evidence supporting this idea has been complex and inconsistent. Evidence from a simpler perceptual task would make clear whether psychotic symptoms are associated with overreliance on prior information and impaired updating.

OBJECTIVE To investigate whether individuals with schizophrenia or schizoaffective disorder (PSZ) and healthy control individuals (HCs) differ in the ability to update their beliefs based on evidence in a relatively simple perceptual paradigm.

DESIGN, SETTING, AND PARTICIPANTS This case-control study included individuals who met DSM-IV criteria for PSZ and matched HC participants in 2 independent samples. The PSZ group was recruited from the Maryland Psychiatric Research Center, Yale University, and community clinics, and the HC group was recruited from the community. To test perceptual updating, a random dot kinematogram paradigm was implemented in which dots moving coherently in a single direction were mixed with randomly moving dots. On 50% of trials, the direction of coherent motion changed by 90° midway through the trial. Participants were asked to report the direction perceived at the end of the trial. The Peters Delusions Inventory and Brief Psychiatric Rating Scale (BPRS) were used to quantify the severity of positive symptoms. Data were collected from September 2018 to March 2020 and were analyzed from approximately March 2020 to March 2021.

MAIN OUTCOMES AND MEASURES Critical measures included the proportion of responses centered around the initial direction vs the subsequent changed direction and the overall precision of motion perception and reaction times.

RESULTS A total of 48 participants were included in the PSZ group (31 [65%] male; mean [SD] age, 36.56 [9.76] years) and 36 in the HC group (22 [61%] male; mean [SD] age, 35.67 [10.74] years) in the original sample. An independent replication sample included 42 participants in the PSZ group (29 [69%] male; mean [SD] age, 33.98 [11.03] years) and 34 in the HC group (20 [59%] male; mean [SD] age, 34.29 [10.44] years). In line with previous research, patients with PSZ were less precise and had slower reaction times overall. The key finding was that patients with PSZ were significantly more likely (original sample: mean, 27.88 [95% CI, 24.19-31.57]; replication sample: mean, 26.70 [95% CI, 23.53-29.87]) than HC participants (original sample: mean, 18.86 [95% CI, 16.56-21.16]; replication sample: mean, 15.67 [95% CI, 12.61-18.73]) to report the initial motion direction rather than the final one. Moreover, the tendency to report the direction of initial motion correlated with the degree of conviction on the Peters Delusions Inventory (original sample: $r = 0.32$ [$P = .05$]; replication sample: $r = 0.30$ [$P = .05$]) and the Brief Psychiatric Rating Scale Reality Distortion score (original sample: $r = 0.55$ [$P = .001$]; replication sample: $r = 0.35$ [$P = .03$]) and severity of hallucinations (original sample: $r = 0.39$ [$P = .02$]; replication sample: $r = 0.30$ [$P = .05$]).

CONCLUSIONS AND RELEVANCE The findings of this case-control study suggest that the severity of psychotic symptoms is associated with a tendency to overweight initial information over incoming sensory evidence. These results are consistent with predictive coding accounts of the origins of positive symptoms and suggest that deficits in very elementary perceptual updating may be a critical mechanism in psychosis.

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Delusions are tenaciously maintained, even in the face of clear disconfirmatory evidence. Similarly, hallucinations are perceptual experiences that occur despite a lack of corresponding external stimuli. Recent accounts suggest that alterations in the integration of prior expectations and new sensory inputs play a role in delusions and hallucinations. At issue is whether these abnormalities arise at the level of perceptual processes or at the level of higher-order reasoning processes. The notion that perception involves inferential processes akin to deliberative reasoning dates to seminal writings and observations of von Helmholtz,¹ who argued that, similar to reasoning, perception involved drawing conclusions about what is likely to exist in the world given sensory evidence. This perspective assumes no sharp boundaries among perception, reasoning, and belief.²⁻⁴

However, many researchers have emphasized the role of higher-level reasoning processes in the genesis of delusional beliefs.^{5,6} This work has highlighted abnormalities in evidence gathering, belief evaluation, the impact of confirmation biases, conflict detection, and the engagement and weighting of intuitive vs analytic reasoning.⁷⁻¹⁰ For example, Woodward et al¹¹ suggested that a bias against integrating disconfirmatory evidence underlies the inflexibility of delusional beliefs. Multiple reports suggest that people with more severe delusions are less likely to modify their initial beliefs when presented with subsequent information.¹²⁻¹⁴ However, these evidence integration paradigms involve multiple complex cognitive processes (language comprehension, reasoning, and working memory) that could affect task performance, which complicates their interpretation.

Paradoxically, there is evidence that patients show excessive belief updating. For example, in the beads task, participants are asked to decide which of 2 hidden jars is the source for a series of beads.¹⁵ Here, patients jump to conclusions, sometimes deciding after seeing only a single bead. In such tasks in which disconfirmatory evidence is presented, patients rapidly shift their judgments, updating based on very limited evidence.¹⁶⁻¹⁹ Therefore, the tendency to jump to conclusions is plausibly implicated in the genesis of unusual beliefs. However, performance on the beads task does not correlate consistently with severity of delusions.^{9,20,21} Thus, belief updating appears to be altered in psychosis, but the relevant paradigms involve multiple cognitive processes, and the direction of the alteration varies across methods.²²⁻²⁴ These tasks involve combinations of multiple cognitive and motivational processes that are altered in schizophrenia or schizoaffective disorder (PSZ), making it difficult to isolate specific deficits in belief updating.

The present study assessed whether aberrant belief updating can be observed in a relatively simple motion perception task that poses minimal demands on conscious reasoning and is well understood at the neural level in primate and rodent models.²⁵ The task was a motion direction estimation paradigm (Figure 1) with random dot kinematogram (RDK) stimuli. In the key trials, 35% of dots move in the same coherent direction for 500 milliseconds and then move in a direction shifted by 90° relative to the initial direction for 500 milliseconds. Participants are instructed to report the direction of motion at the end of the trial. We hypothesized that patients with PSZ would favor initial evidence relative to subse-

Key Points

Question Are psychotic symptoms related to failures in perceptual updating?

Findings In this case-control study of 160 participants in 2 independent samples, perceptual updating was assessed via a random dot motion perception task in which motion direction changes midway through a trial, and participants were asked to report the direction at the end of the trial. Individuals with schizophrenia tended to overreport the direction of the initial motion rather than the changed motion direction as instructed, which was associated with the severity of delusions and hallucinations.

Meaning The findings of this study suggest that failure to integrate new sensory evidence with prior knowledge may be associated with psychotic symptoms in schizophrenia.

quent sensory evidence, leading them to incorrectly report the initial motion direction on motion-change trials, and that this tendency would be associated with more severe positive symptoms. Such a finding would provide evidence that impaired perceptual updating plays a role in psychotic symptoms.

Methods

Participants

In this case-control study, we tested 48 clinically stable individuals meeting *DSM-IV-TR* criteria for PSZ²⁶ and 36 matched healthy control (HC) participants recruited from the outpatient clinics of the Maryland Psychiatric Research Center, Baltimore, and via internet and print advertisements. In a second independent replication sample, we tested 42 patients with PSZ and 34 HC participants, most of whom were recruited at Maryland Psychiatric Research Center, with others recruited at Yale University, New Haven, Connecticut, and community clinics. This protocol was approved by the institutional review board at the University of Maryland, Baltimore, and Yale University, and all participants gave written informed consent before taking part in the study. Participant characteristics are summarized in the Table. This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline.

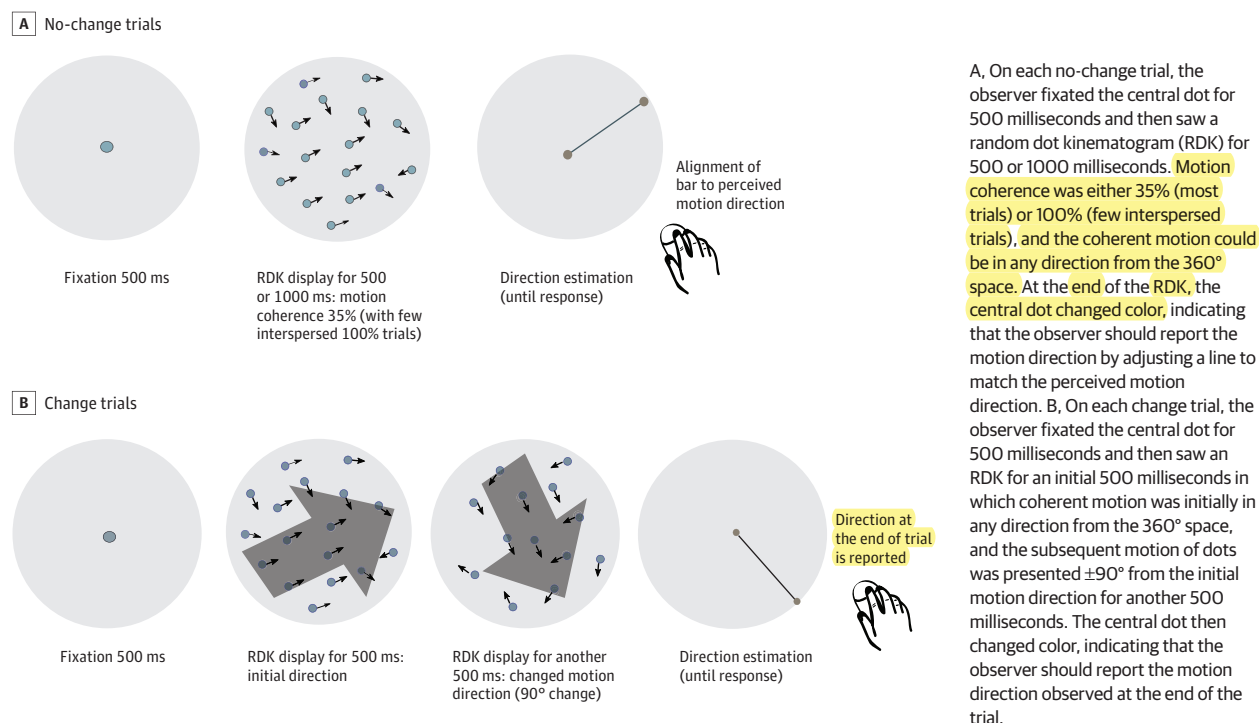
Neuropsychological and Symptom Measures

Data for this study were collected from September 2018 to March 2020. We used the Measurement and Treatment Research to Improve Cognition in Schizophrenia Consensus Cognitive Battery²⁷ and the Wide Range Achievement Test 4²⁸ to assess current and premorbid cognitive functioning. We administered the Brief Psychiatric Rating Scale (BPRS)²⁹ to quantify symptom severity in PSZ and the Peters Delusions Inventory (PDI)³⁰ to quantify delusional beliefs in both the PSZ and HC groups.

Stimuli and Procedure

As illustrated in Figure 1, participants were asked to report the direction of a coherent motion signal in an RDK.³¹ Stimuli were

Figure 1. Results of No-Change and Change Trials



35% coherent (ie, proportion of dots moving coherently relative to those replotted randomly) on 85% of trials, with the remaining 15% of trials being “catch trials.” All directions were equiprobable, and observers were instructed to report the direction of motion at the end of the trial by using a mouse to adjust a bar to match the perceived motion direction. There were 2 trial types: (1) no-change trials, in which motion direction stayed constant through 500 or 1000 milliseconds of stimulus presentation, and (2) motion change trials (always 1000 milliseconds) wherein the direction of motion changed by -90° or $+90^\circ$, resulting in 500 milliseconds of initial direction, followed by 500 milliseconds of changed direction. The motion was continuous during the period of a given trial, with no break when the direction changed.

At 35% coherence, we administered 192 change trials and 192 no-change trials (half at each duration). Participants also completed 24 catch trials (100% coherence) for each of the change/no-change 500-millisecond and no-change 1000-millisecond trial types, allowing us to verify that participants understood the instruction. Trial types were presented in random order. Further details of the stimuli, procedure, and apparatus are described in eMethods 1 in the Supplement.

Statistical Analysis

Data were analyzed from approximately March 2020 to March 2021. All statistical tests were 2 tailed ($\alpha = .05$). Key measures included (1) proportion of responses centered ($\pm 15^\circ$) around the target direction angle (the direction of motion at the end of the trial), (2) proportion of responses centered ($\pm 15^\circ$) around the initial motion direction, and (3) lapse rate (responses reflecting random guesses or attentional lapses). Details on how these

measures were quantified are provided in the Data Analysis subsection of eMethods 1 in the Supplement.

For the no-change trials, each measure was analyzed in a 2-way analysis of variance with factors of group (PSZ vs HC) and duration of RDK presentation (500 or 1000 milliseconds). For the change trials, which were always 1000 milliseconds in duration, between-group differences were assessed using 3 independent groups *t* tests with a Bonferroni-adjusted α level of .016 per test. We used Cohen *d* as a measure of effect size and Pearson correlations to examine relationships among measures. We conducted separate analyses of the 2 samples of participants.

Results

Change Trials (35% Coherence) Response Proportions

A total of 48 participants were included in the PSZ group (31 [65%] male and 17 [35%] female; mean [SD] age, 36.56 [9.76] years) and 36 participants in the HC group (22 [61%] male and 14 [39%] female; mean [SD] age, 35.67 [10.74] years) in the original sample. The independent replication sample included 42 participants in the PSZ group (29 [69%] male and 13 [31%] female; mean [SD] age, 33.98 [11.03] years) and 34 participants in the HC group (20 [59%] male and 14 [41%] female; mean [SD] age, 34.29 [10.44] years). Figure 2 shows the results from the change trials. The PSZ group had a lower proportion of target responses in the original sample ($t = 5.34$; $P < .001$; Cohen $d = 1.18$) and in the replication sample ($t = 2.79$; $P = .007$; Cohen $d = 0.64$). The PSZ group also had a higher proportion of lapses than the HC group in the replication sample ($t = -2.78$; $P = .01$; Cohen $d = -0.64$), but this difference was not signifi-

Table. Participant Characteristics

	Participant group ^a							
	Original sample				Replication sample ^b			
Characteristic	PSZ (n = 48)	HC (n = 36)	Statistic	P value	PSZ (n = 42)	HC (n = 34)	Statistic	P value
Demographics								
Age, y	36.56 (9.76)	35.67 (10.74)	t = 0.40	.69	33.98 (11.03)	34.29 (10.44)	t = 0.20	.85
No. female/male	17/31	14/22	χ ² = 0.10	.74	13/29	14/20	χ ² = 0.86	.35
Race and ethnicity, No. Black/White/other ^c	18/24/6	16/16/4	χ ² = 0.41	.81	14/23/5	5/20/9	χ ² = 4.83	.09
Educational attainment, y								
Participant	13.54 (2.27)	15.54 (2.32)	t = 3.93	<.001	13.18 (3.16)	15.38 (3.64)	t = 2.82	.006
Maternal	14.24 (2.76)	14.40 (3.58)	t = 0.95	.35	16.24 (1.99)	14.10 (2.25)	t = 1.52	.13
Paternal	13.66 (4.16)	12.89 (5.84)	t = 0.94	.35	15.44 (3.58)	14.83 (2.75)	t = 1.01	.32
Neurocognitive test results								
WRAT-4	97.77 (14.2)	110.37 (14.17)	t = 3.98	.001	103.22 (23.33)	117.11 (9.39)	t = 2.95	<.001
MD								
Processing speed	38.40 (14.64)	54.03 (8.49)	t = 5.58	<.001	42.25 (15.60)	53.86 (16.76)	t = 2.78	.01
Working memory	38.23 (11.09)	51.94 (8.88)	t = 5.96	<.001	42.38 (16.30)	52.79 (13.68)	t = 2.66	.01
Verbal learning	38.34 (9.33)	49.97 (10.25)	t = 5.31	<.001	40.28 (15.41)	48.32 (12.49)	t = 2.20	.03
Visual learning	37.11 (14.35)	47.76 (7.83)	t = 3.92	<.001	NA	NA	NA	NA
Reasoning	43.45 (11.06)	51.85 (8.58)	t = 3.70	<.001	NA	NA	NA	NA
Social cognition	40.17 (12.26)	52.38 (8.58)	t = 4.99	<.001	NA	NA	NA	NA
Attention vigilance	40.04 (12.09)	49.09 (11.74)	t = 4.37	<.001	NA	NA	NA	NA
MCT overall	32.77 (14.4)	50.24 (11.81)	t = 6.87	<.001	NA	NA	NA	NA
Ratings								
PDI								
Conviction	3.25 (0.19)	1.91 (0.30)	t = 24.99	<.001	3.67 (0.87)	1.82 (1.87)	t = 5.26	<.001
Distress	3.00 (0.16)	0.93 (0.14)	t = 61.85	<.001	2.39 (1.10)	1.10 (1.17)	t = 4.49	<.001
Preoccupation	3.01 (0.18)	1.41 (0.20)	t = 38.44	<.001	3.22 (0.74)	1.14 (1.18)	t = 8.67	<.001
Total	11.16 (1.35)	2.15 (0.42)	t = 38.61	<.001	9.47 (6.69)	2.17 (2.63)	t = 5.54	<.001
Clinical ratings								
BPRS								
Positive symptoms	2.3 (1.21)	NA	NA	NA	2.50 (1.24)	1.01 (0.05)	t = 6.33	<.001 ^d
Negative symptoms	1.61 (0.52)	NA	NA	NA	1.78 (0.89)	1.02 (0.10)	t = 4.53	<.001 ^d
Disorganized symptoms	1.25 (0.27)	NA	NA	NA	1.30 (0.42)	1.01 (0.04)	t = 3.69	<.001 ^d
Total score	34.83 (9.38)	NA	NA	NA	35.12 (9.59)	21.29 (1.61)	t = 7.54	<.001 ^d
Antipsychotic medication								
CPZ dose equivalent, mg/d	486.53 (403.93)	NA	NA	NA	418.33 (362.12)	NA	NA	NA
Duration of illness, y ^e	14.04 (9.86)	NA	NA	NA	10.15 (10.65)	NA	NA	NA

Abbreviations: BPRS, Brief Psychiatric Rating Scale; CPZ, chlorpromazine equivalent; HC, healthy control; MCT, Measurement and Treatment Research to Improve Cognition in Schizophrenia Consensus Cognitive Battery (MCCB) Composite Total; MD, MCCB cognitive domain; NA, not applicable; PDI, Peters Delusions Inventory; PSZ, schizoaffective disorder; WRAT-4, Wide Range Achievement Test 4.

^a Unless otherwise indicated, data are expressed as mean (SD).

^b Fifteen participants in sample 2 (10 HCs and 5 patients with PSZ) were

recruited at Yale University, New Haven, Connecticut.

^c Data were self-reported. Other category includes Asian, Native Hawaiian or Other Pacific Islander, or 1 or more (mixed).

^d Ratings were available for 39 patients with PSZ and 30 HCs.

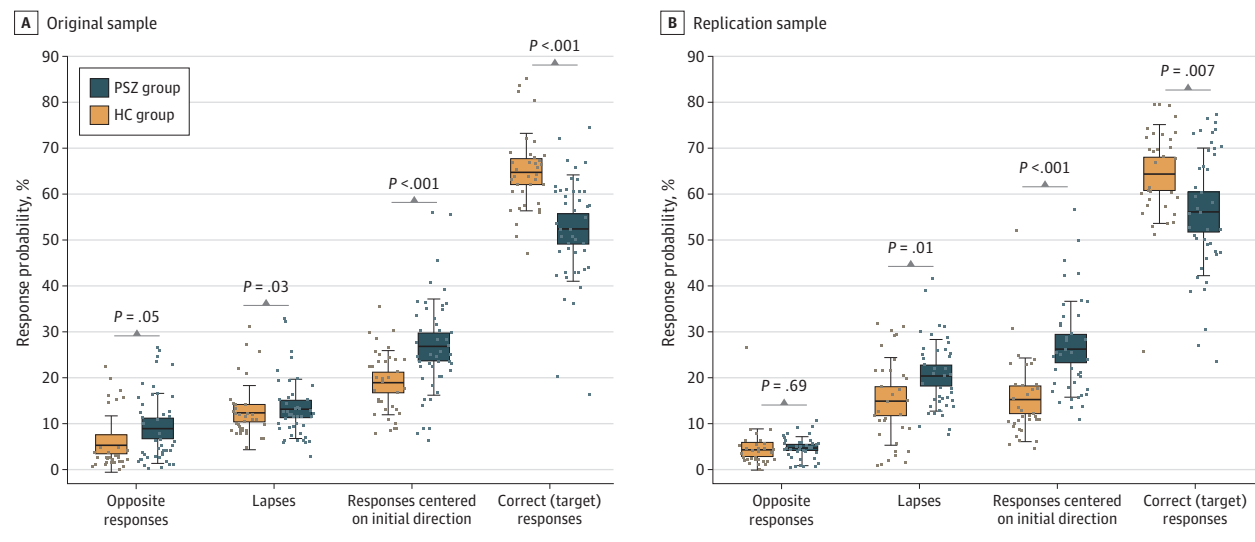
^e This information was available for 30 patients with PSZ in the original sample and 40 patients with PSZ in the replication sample.

cant at the corrected α level in the original sample ($t = -2.16$; $P = .03$; Cohen $d = -0.46$). The key result was that patients with PSZ often failed to update to the changed direction: they had a higher proportion of responses that were centered on the initial motion direction relative to HC participants in the original sample (PSZ mean, 27.88 [95% CI, 24.19-31.57]; HC mean, 18.86 [95% CI, 16.56-21.16]; $t = -3.90$; $P < .001$; Cohen $d = -0.83$) and in the replication sample (PSZ mean, 26.70 [95% CI, 23.53-29.87]; HC mean, 15.67 [95% CI, 12.61-18.73]; $t = -4.84$; $P < .001$; Cohen $d = -1.12$). Patients with PSZ were also less precise than HC participants (Figure 3C and D), quan-

tified as greater mean response error in the original sample ($t = -3.69$; $P < .001$; Cohen $d = -0.81$) and in the replication sample ($t = -2.14$; $P = .04$; Cohen $d = -0.49$).

We also examined response times separately in trials for which the initial and final motion direction was reported (eMethods 7 in the Supplement). The difference between response times for initial motion reports vs changed motion reports was significantly larger in the PSZ group ($t = 4.87$; $P < .001$; Cohen $d = 1.11$) than in the HC group ($t = 3.16$; $P = .002$; Cohen $d = 0.67$). Specifically, patients with PSZ had faster response times when reporting the direction of initial motion

Figure 2. Response Probabilities for Change Trials



To quantify responses for change trials, we derived the proportions of responses centered around the opposite direction from the target (changed) motion direction, lapse rates, proportion of responses centered around initial motion direction, and proportion of responses centered around the target direction (the direction of motion at the end of the trial). Each filled circle represents the proportion for a single participant. These points are layered over a 1.96 SEM (95% CI) in the boxplot and over a 1-SD vertical line, with mean

group proportion indicated as a horizontal line within each boxplot. The group with schizophrenia and schizoaffective disorder (PSZ) had a lower proportion of target responses and a higher proportion of lapses than did healthy controls (HCs). Importantly, patients with PSZ often failed to update to the changed direction; they had a higher proportion of responses that were centered on the initial motion direction relative to HCs.

than when reporting the direction of the changed motion, suggesting that the decision was reached more rapidly in patients with PSZ than in HC participants, consistent with greater weighting of initial evidence in PSZ.

No-Change Trials (35% Coherence) Response Proportions

Statistical analyses of the no-change trials are provided in eMethods 6 in the Supplement, along with reaction time results. Compared with HC participants, patients with PSZ had (1) longer reaction times, (2) a lower proportion of responses centered on the target direction, (3) more lapses, and (4) less precision in their motion reports (eMethods 5 in the Supplement). The group by target duration interaction was not significant in either sample, suggesting that poorer performance in the PSZ group was not attributable to slowing in perceptual processing or impaired working memory. Although patients with PSZ were impaired in their motion processing relative to HC participants in the no-change condition, their deficit relative to HC participants was similar with both the 500- and 1000-millisecond stimulus presentations.

Correlation Analyses

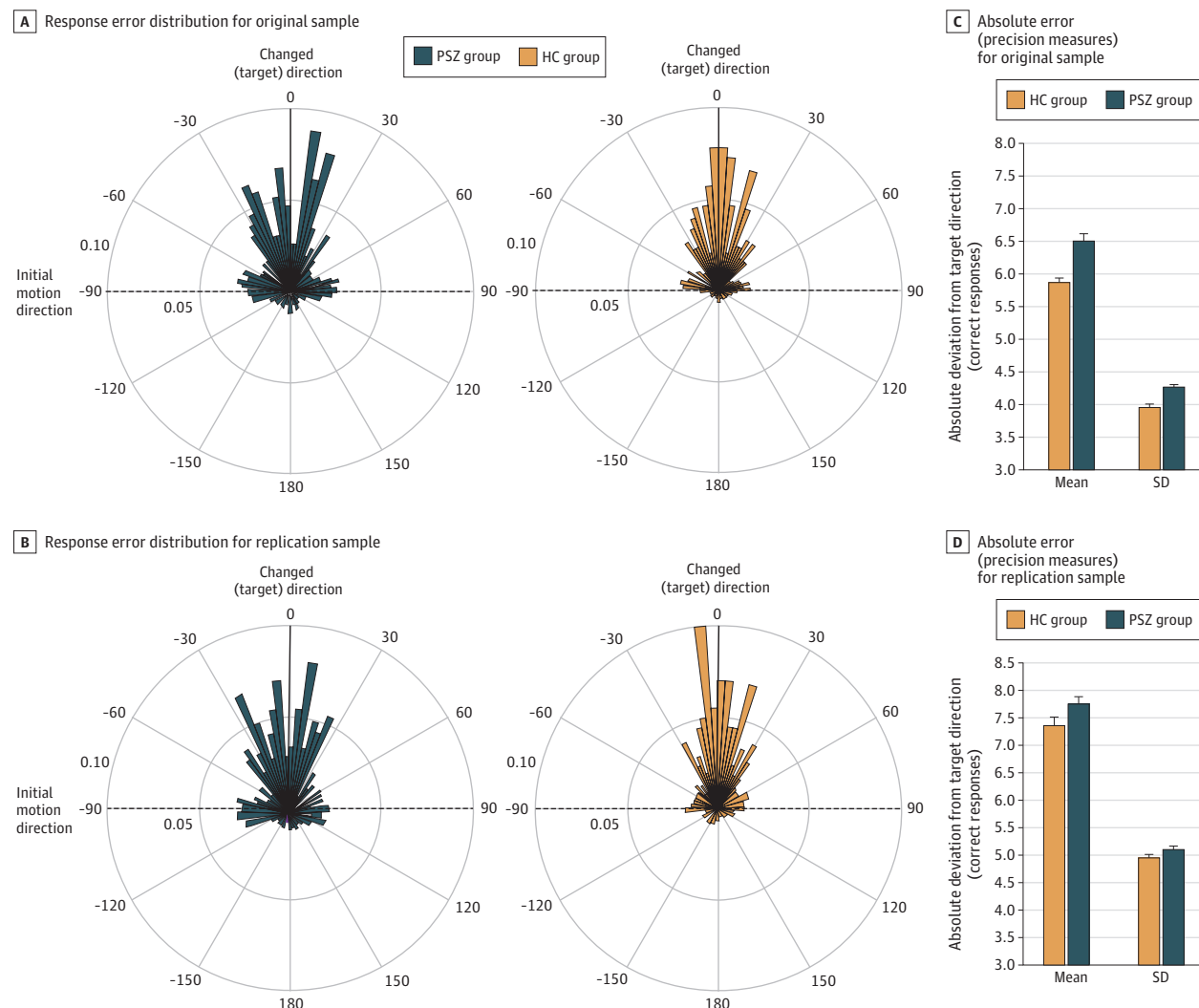
To examine the correlation between updating and symptoms, we used regression models with backward elimination to assess the association between the proportion of initial motion reports and aspects of psychosis, namely the PDI total score, PDI conviction score, BPRS Reality Distortion,³² disorganization, negative symptom factors, and BPRS total score. In the combined patient sample, BPRS Reality Distortion scores were significantly associated with the accuracy of motion direction reports ($t = 3.79$; $P < .001$), whereas the associations between mean PDI conviction ratings

and the accuracy of motion direction reports were not ($t = 1.93$; $P = .06$) (see Figure 4 for illustration of the univariate correlations for the BPRS Hallucination rating and eTables 1 and 2 in the Supplement for the full set of correlations). In the original sample, both PDI conviction ($t = 2.52$; $P = .02$) and BPRS Reality Distortion ($t = 4.42$; $P < .001$) scores were significantly associated with the accuracy of motion direction reports. In the replication sample, only the BPRS Reality Distortion score factor remained significant ($t = 2.44$; $P = .02$). These analyses all suggest that psychosis severity is associated with failures of perceptual updating. Further, these associations were not simply a consequence of poor performance per se: we did not observe a significant correlation between lapse rate and psychosis severity or between lapse rate and increased initial motion reports, nor did we observe any negative correlation between accuracy (proportion of responses centered around the target) on the no-change trials and psychosis severity. There were no associations between task measures and duration of illness or medication (see eMethods 8 in the Supplement).

100% Coherence Trials

Results from 100% coherence trials demonstrate that all participants in both groups understood the instruction to report the final direction of motion: 70% to 80% of responses in the original sample (PSZ group mean, 70.07 [95% CI, 65.4-74.7]; HC group mean, 76.71 [95% CI, 71.3-82.1]) and in the replication sample (PSZ group mean, 73.66 [95% CI, 69.8-77.5]; HC group mean, 79.82 [95% CI, 76.5-83.1]) were centered around the changed direction in the HC and PSZ groups, respectively (see eMethods 4 in the Supplement; above chance at statistically significant levels, $P < .01$ for original and replication samples in the PSZ and HC groups). Across both samples, the proportion of responses centered around

Figure 3. Response Error Distributions and Absolute Error Precision Measures



A and B, Behavioral performance was quantified as the response error (the angular difference between the true motion direction and the reported motion direction) for each trial. The rose plots show the distributions of response errors for each group for the motion change trials. The rose plots have been rotated so the target (changed) motion direction appears at the top (12 o'clock) position, whereas the initial motion position appears 90° to the left or right (9 o'clock and 3 o'clock positions, respectively). Most response errors were clustered around 0°, with smaller clusters around the initial motion direction ($\pm 90^\circ$). C and D, To

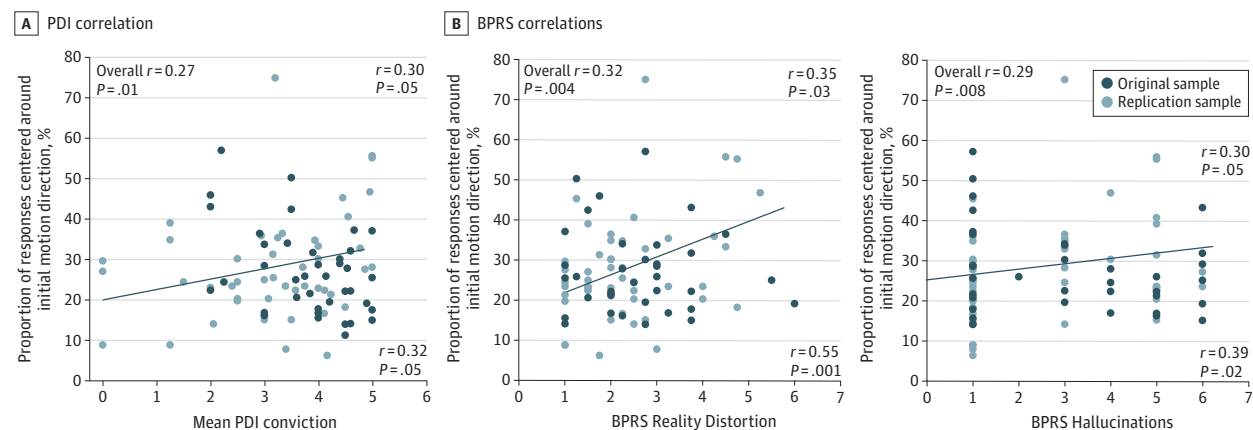
quantify precision of responses, the absolute mean error around accurate trials (ie, trials that were marked to be centered around changed/target motion direction) was derived. The bar plots represent mean response errors and SDs. For responses that were centered around the correct (changed) motion direction, in both samples, the absolute magnitude of response error was larger in patients with schizophrenia or schizoaffective disorder (PSZ) than healthy control (HC) participants. The variability (SD) of this response error was not significantly different between groups.

initial motion direction was zero in most participants (59 of 70 HCs and 72 of 90 patients with PSZ). To ensure that the results in the 35% condition did not reflect a failure to understand the task or a general impairment in reporting the second of 2 stimulus intervals, we performed an additional analysis in which we only included this subset of participants who made 0 errors in the 100% change condition. Critically, as with the full set of participants, patients with PSZ had a higher proportion of responses centered on the initial motion direction relative to HC participants in the original sample ($t = -4.32$; $P < .001$; Cohen $d = -1.03$) and the replication sample ($t = -4.99$; $P < .001$; Cohen $d = -1.29$).

Discussion

In this case-control study, patients with PSZ exhibited failures of perceptual updating, even in a low-level task, and these failures were correlated with psychotic symptoms. These findings were replicated in a second sample including participants tested by different researchers at a different site, enhancing confidence in the generalizability of our results. Critically, patients with PSZ were more likely than HCs to report the direction of initial motion on the motion change trials, failing to update their perceptual rep-

Figure 4. Correlation of Responses



A, Scatterplot for Peters Delusions Inventory (PDI) illustrates the correlation between the proportion of responses around initial motion direction and the PDI conviction measure (which captures strength of delusional beliefs) in patients with schizophrenia or schizoaffective disorder (PSZ) from both samples. B, Scatterplots for the Brief Psychiatric Rating Scale (BPRS) illustrate the correlation between the proportion of responses around initial motion direction and the BPRS Reality Distortion scores in patients with PSZ from both

samples. The BPRS Reality Distortion measure (left) captures individual symptoms such as grandiosity, suspiciousness, hallucinations, and unusual thought content. This scatterplot demonstrates that the severity of psychotic symptoms is associated with a tendency to overweight initial information. We also observed that the univariate correlation between the proportion of responses around initial motion direction and the BPRS Hallucinations score (right) was significant in both PSZ samples.

representations in light of new evidence. Further, this failure to update was associated with the severity of positive symptoms. Moreover, PSZ performance on 100% coherence trials indicated that this effect was unlikely to be due to poor comprehension of instructions. Overall, consistent with prior literature on motion processing, patients with PSZ exhibited poorer integration of spatially distributed motion signals than did HC participants,³³ suggesting impairments in early visual processing. Previous studies have found that cortical processing in the early visual system, especially the magnocellular pathway, is deficient in schizophrenia.³⁴ However, there is no reason to expect that these deficits would produce a bias to report the initial motion direction.

These results demonstrate that even in a relatively simple perceptual paradigm, patients with PSZ fail to update their perceptual beliefs when faced with new information, echoing previous observations.³⁵ The fact that the degree of updating failure in this simple perceptual task was correlated with positive symptoms and degree of delusional conviction suggests that the severity of psychosis may reflect a fundamental alteration of basic perceptual and cognitive processes.

Moreover, the RDK paradigm is widely used in animal models, providing a potential tool to be used in translational treatment development research guided by a mechanistic model of symptom formation. We know of no animal studies using motion-change trials examined in the present study, but future work could include this manipulation. Methodological advances in human neurophysiological investigations^{36,37} and computational work³⁸ have enabled progress in understanding of the neural underpinnings of decision-making that both complement and expand the knowledge gained through invasive recordings in animals. The possibility of integrating findings from noninvasive electroencephalographic and/or magnetoencephalographic recordings with preclinical research could potentially lead to the identification of pathophysiological mechanisms and novel treatment targets.

The present findings are consistent with hierarchical bayesian predictive coding accounts of psychosis.^{4,39,40} These accounts propose that perception is a form of inference, combining prior beliefs and sensory evidence weighted by their reliability or inverse variance. Further, these accounts have emphasized that prior knowledge at low and high hierarchical levels may be differentially affected in psychotic illness. Previous studies have examined perceptual inference deficits in patients with PSZ through complex cognitive tasks that tap higher-level reasoning. Multiple experiments suggest that prior beliefs may be overweighted, particularly in individuals with severe psychotic symptoms.^{35,41-44} Such prior overweighting manifests in our data as an overreliance on the initial motion direction and the failure to update during some of the motion change trials. To our knowledge, our study is the first to observe behavior resembling analytic reasoning in a low-level task that does not require extensive learning, overt strategizing or deliberation, or integration of multiple cues or sources of information.

Our findings are also consistent with an “all-or-none” style of updating. Nassar et al,⁴⁵ using a probabilistic reinforcement learning task, reported that patients with PSZ showed an all-or-none style of updating. That is, patients with PSZ failed to update on many trials when they experienced a prediction error, whereas on other trials, they fully updated based on a single instance of an unexpected outcome. Although our task did not involve learning, as did that of Nassar et al,⁴⁵ the tendency toward all-or-none updating appears to describe our results as well: in some change trials, patients with PSZ reported the final direction (all), but in others they reported the initial direction (none) (Figure 2A).

In another study, Schmack et al⁴⁴ reported a failure of perceptual maintenance across a short delay (all updating) and an inordinate influence of instructed beliefs on perceptual inference (no updating). Both phenomena correlated with PDI con-

viction scores, as did the updating failures in our data set. Taken together, the findings across studies are not consistent with a general tendency to overweight or underweight prior knowledge. Instead, we suggest that the illness compromises bayesian inference more generally, relating perhaps to perturbed weighting of data streams by their reliability and compensatory reliance on other sources of information when drawing conclusions.⁴⁶ Our results stand in contrast to those of Valton et al,⁴⁷ who used a motion direction detection paradigm with stimuli presented at a near-individualized contrast threshold. In their study, 1 motion direction was presented more frequently, which created a reporting bias, but this bias was similar in patients and HC participants, indicating equivalent use of prior evidence. We suspect that the use of near-threshold stimuli by Valton et al may have resulted in their patients adopting a more conservative response bias, which would explain why they did not observe the same use of prior knowledge that we observed in our study.

An alternate explanation in our study might be that patients with PSZ are more prone to report the initial motion direction because they have slowed processing speed and simply did not have enough time to process the second motion direction. This explanation is unlikely, however, because there was no group by duration interaction effect on motion accuracy in the no-change trials. Furthermore, slowing would favor reporting the second motion direction, because the first motion direction was masked by the second motion direction. Similarly, increased reports of initial motion direction are unlikely to be attributable to lapses of attention. Our modeling approach provided an estimate of lapse rate (eMethods 2 and eMethods 3 in the Supplement) wherein the lapse parameter was indeed higher in patients. However, it is difficult to consider an accurate report of the initial direction of motion as reflecting a random response that might arise from an attentional lapse. However, lapses would lead to random responses, not an accurate report of the initial direction of motion. Furthermore, our task did not require participants to

remember the initial direction or to detect changes in direction per se, so the task did not put any more demand on working memory than more typical perceptual tasks. It is also noteworthy that the direction of the effect is the opposite of what would be expected based on reduced working memory capacity in PSZ: although patients with PSZ have reduced working memory capacity, they were more likely than HCs to retain the motion direction from the first interval.

Another possibility that has emerged from perceptual decision-making studies⁴⁸⁻⁵¹ is that patients manifested temporal integration problems, with an exaggeration of the normal tendency to make responses biased toward information presented earlier in time, as shown by Kalisvaart et al⁵² in an experiment using very briefly presented sequential stimuli. Given the large differences in experimental design, it seems unlikely that the information integration observed by Kalisvaart et al⁵² can explain increased reports of initial motion direction seen herein. Further study is needed to investigate the association between temporal integration and bayesian models of perception.

Limitations

A major limitation of this study is that we were only able to account for a limited amount of variance in psychosis severity. This limitation is shared with nearly all other behavioral studies reporting on correlates of psychosis.

Conclusions

The results of this case-control study—which were fully replicated in a second sample—suggest that the RDK paradigm taps an important mechanism for understanding psychotic symptoms. Although our ability to account for variance in psychosis severity was limited, these data suggest that the processes involved in accumulating, evaluating, and updating evidence are reliably implicated in psychosis and that these processes can be assessed using simple perceptual judgment paradigms.

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Correction: This article was corrected on January 12, 2022, to change 3 instances of the incorrect term *white matter* to the correct term *working memory* in the Discussion section.

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