As we recollect past events (episodic memory), we can unfold an entire sequence of experiences happening at a particular place and time. Neuroscience highlighted the fact that this ability to encode and recall sequences of events serves several purposes beyond retrieval of past events. Past information is often useful for generating predictions helping us navigate an uncertain world. For instance, imagine watching a basketball game the first time. When a player gets a basket, the score for that player’s team goes up. Therefore, the next time a player shoots the ball into the basket, prior knowledge allows us to predict that the score will increase. Humans can be remarkably effective learning about arbitrary sequences of stimuli (1), and information about learned sequences can help us anticipate and efficiently process information even when explicit episodic memory retrieval is not required (2,3).

Episodic memory is impaired in people with schizophrenia (SZ). Although SZ affects a range of cognitive abilities, episodic memory is disproportionately impaired, and the severity of memory deficits predicts patients’ ability to work and live independently (4). A key finding is that people with SZ can sometimes perform well at recognizing familiar objects or events but are especially impaired at remembering relationships between objects and the context in which they were encountered (5-9). Results from functional magnetic resonance imaging (fMRI) studies suggest two possible explanations for these deficits. In one view, dysfunction might reflect impaired functioning of the hippocampus, which normally supports the ability to bind item and context information in a manner that can support episodic memory (2,10). Another explanation, which is not mutually exclusive (11), is that prefrontal dysfunction affects control processes that enable one to use learned information to make complex attributions about the context in which events take place (12,13).

Whereas studies of memory emphasize memory for past events, other work has focused on the idea that people with SZ might be impaired generating precise predictions about the future (14,15). Bayesian models propose that in the healthy brain, higher-order brain areas generate predictions about
upcoming sensory information and experience prediction errors encouraging belief updating and better future predictions (14,16–18). In this framework, people with SZ generate aberrant prediction errors impairing their learning about the statistical structure of the world. Prediction error research in SZ has informed a broad range of paradigms, including mismatch negativity (19), examination of hallucinations (20), and studies of reinforcement learning, demonstrating impaired learning (21) and dysfunction in the dorsal and ventromedial prefrontal cortex and striatum (22,23).

At present, it is not clear whether people with SZ show more global deficits in the ability to predict future events based on learned memory representations. Although studies have shown deficits in explicit memory for temporal or sequential relationships, these deficits might reflect an inability to make complex memory attributions rather than a prediction deficit per se. Accordingly, in this study, we investigated the extent to which people with SZ were able to use memory of learned sequences to successfully predict future events.

We adapted a paradigm from a recent study of healthy undergraduates that scanned participants while they were making semantic decisions about sequences of objects (24). In some sequences, object order was fixed, such that seeing the first object could enable generation of precise predictions about the remaining objects in the sequence. In other sequences, object order was changed on every repetition (i.e., random), allowing participants to become highly familiar with the objects but unable to make accurate predictions. With this paradigm, healthy individuals had faster reaction times (RTs) when making semantic decisions about objects in fixed versus random sequences. Thus, after a sequence was learned, people used that sequence memory to facilitate response preparation by predicting upcoming objects during fixed sequences, resulting in faster semantic decisions.

Previously (3), we used electroencephalography (EEG) to examine sequence learning and found that both healthy control (HC) subjects and individuals with SZ reached criterion for sequence learning and used sequence memory to predict future objects and make faster semantic decisions for objects in fixed versus random sequences. This RT facilitation is referred to as the sequence prediction effect. Although people with SZ also reached criterion during sequence learning, their learning was less efficient and accompanied by decreased alpha and beta-1 power prior to stimulus onset for fixed versus random sequences (3). These frequency bands have also been found to mediate prediction feedback (14).

Here, we report the second part of this study, in which fMRI was used to identify brain regions that might underlie hypothesized deficits in sequence-based prediction in SZ (Figure 1). Based on previous work, we focused on 2 regions of interest (ROIs): the dorsolateral prefrontal cortex (DLPFC), identified as dysfunctional during relational memory in fMRI studies of SZ (25), and the right posterior hippocampus, identified as a key region mediating sequence representation in our previous sequence memory study (24). Using representational similarity analysis (RSA), we examined the extent to which activity patterns in these regions carried position information for objects in learned sequences and whether the fidelity of these representations could identify individual differences in sequence-based item prediction for fixed versus random sequences. We hypothesized that neural sequence representations in DLPFC and posterior hippocampus would be disrupted in people with SZ, resulting in attenuated sequence prediction effects.

METHODS AND MATERIALS

Participants

As published previously (3), 44 individuals (7 unmedicated with SZ were recruited from the University of California Davis Early Psychosis Programs (EDAPT and SacEDAPT). A total of 66 HC subjects responded to paid advertisements through the UC Davis Imaging Research Center. Clinical assessments were conducted to confirm SZ diagnosis and symptom severity. Clinicians with master’s or doctoral level training confirmed the diagnosis using the Structured Clinical Interview for DSM-V. Symptoms were assessed using the Brief Psychiatric Rating Scale, Scale for the Assessment of Negative Symptoms, and Scale for the Assessment of Positive Symptoms. Exclusion criteria included substance abuse in the past year, implants that may interfere with MRI scanning (e.g., ferromagnetic implants), neurologic defects, loss of consciousness after head trauma, low IQ (i.e., <70), or <20/30 vision when corrected. Four participants were excluded for miscellaneous reasons including a change in diagnosis (1 HC, 1 SZ), an incidental finding (1 SZ), and refusal to enter the study.

![Figure 1](www.sobp.org/BPCNNI)

**Figure 1.** Schematic of the paradigm. Fixed sequences show the same objects in the same position for each repetition. Random sequences show the same objects but in a different position each repetition.
scanner due to anxiety (1 SZ). A total of 11 participants (7 HC, 4 SZ) were excluded due to operator error, which caused a misalignment of task onset and scanner onset. An additional 6 participants (2 HC, 4 SZ) were excluded due to poor quality behavioral data (>30% nonresponses), and 4 participants (2 HC, 2 SZ) were excluded for low-quality structural/functional scans (signal dropout or excess motion >1 voxel). Following exclusions, data are presented for a final sample of 85 participants (54 HC and 31 SZ). As seen in Table 1, groups were matched on age, gender, and parental education, but the SZ sample had lower participant education because illness often interrupts educational attainment. Included in the table are chlorpromazine equivalents for medicated participants with SZ. This study was approved through the University of California Davis Institutional Review Board, and participants provided informed consent prior to study.

Procedure and Design

Encoding Phase. Participants learned 5 sequences [see (24)] during EEG (3) prior to entering the MRI scanner. Encoding conditions are illustrated in Figure 1, and details are provided in Zheng et al. (5).

Sequence Retrieval Task. Immediately following encoding, participants were positioned in the MRI scanner. During sequence retrieval, participants viewed previously encoded sequences (2 fixed, 2 random, and 1 novel) for 3 repetitions per run across 4 runs. Sequence order was randomized and objects appeared in a continuous stream, with no delays between sequences. Each object in each sequence was presented for 1000 ms. Before each run, a semantic question was provided, which participants answered for each object. Questions were 1) Can this object fit in a shoebox? 2) Can you easily lift this object with one hand? 3) Is the presented object living? or 4) Does this object contain visible metal? Semantic questions were asked to maintain attention and gauge RT differences both within and between sequences to index sequence prediction success.

MRI Acquisition

Imaging was conducted at the University of California Davis Imaging Research Center on a 3T Siemens Trio Total imaging matrix MRI system with a 32-channel head coil. Structural images were acquired using a T1-weighted magnetization-prepared rapid acquisition gradient-echo pulse sequence (208 slices, sagittal; voxel size = 1.0 mm^3; repetition time = 2000 ms; echo time = 2.98 ms; flip angle = 8°; field of view = 256 mm^2). Functional images were acquired with an echo planar imaging sequence (34 slices, interleaved; 235 time points; voxel size = 3.4 mm^3; repetition time = 2000 ms; echo time = 25 ms; field of view = 218 mm^2).

Data Processing and Analysis

Behavioral Data. Sequence prediction effects were calculated by averaging RT across objects 2 to 5 for fixed and random sequences and calculating differences in RT between sequence types (fixed vs. random). Repeated-measures analysis of variance (ANOVA) identified main effects of group (HC vs. SZ), sequence type (fixed vs. random), or higher-order interactions for averaged RT values. Pearson product moment correlations examined associations between symptom severity (total scores on the Brief Psychiatric Rating Scale, Scale for the Assessment of Negative Symptoms, and Scale for the Assessment of Positive Symptoms) and sequence prediction effects. Significance levels were set at p < .05 for all analyses.

fMRI Data Preprocessing. Preprocessing of fMRI data was modeled after Hsieh et al. (2). Preprocessing was accomplished using fMRI Expert Analysis Tool (FSL version 5.0.9). To strip the skull and remove any nonbrain tissue, the Brain Extraction Tool extracted brain volumes. All functional images were slice-time corrected and high-pass filtered with a 0.01-Hz cutoff. MCFLIRT was used for motion correction, and functional images were coregistered with each individual’s magnetization-prepared rapid acquisition gradient-echo using FLIRT. Resulting transformation matrices were used to transform ROIs into native space for each participant.

Regions of Interest. A priori ROIs were the bilateral DLPFC and bilateral hippocampus. Hippocampal ROIs used probabilistic maps based upon an average of 55 hand-traced T1 images using methods validated by Ritchey et al. (10). Hippocampal ROIs included the full body and subregions for head, body, and tail based on anatomical landmarks (10). The DLPFC ROI (36 voxels) used a probabilistic mask, including Brodmann areas 9 and 46, based upon Talairach coordinates.

Table 1. Sample Demographics

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Healthy Control Subjects, n = 54</th>
<th>Individuals With Schizophrenia, n = 31</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, Years</td>
<td>24.10 ± 4.38</td>
<td>23.05 ± 4.23</td>
<td>.28</td>
</tr>
<tr>
<td>Sex, Female/Male</td>
<td>28%/72%</td>
<td>19%/81%</td>
<td>.39</td>
</tr>
<tr>
<td>Education, Years</td>
<td>15.07 ± 1.98</td>
<td>13.50 ± 1.80</td>
<td>.00047*</td>
</tr>
<tr>
<td>Parental Education, Years</td>
<td>13.70 ± 3.03</td>
<td>14.69 ± 2.57</td>
<td>.13</td>
</tr>
<tr>
<td>BPRS, Total Score</td>
<td>–</td>
<td>37.77 ± 10.09</td>
<td>–</td>
</tr>
<tr>
<td>SANS, Total Score</td>
<td>–</td>
<td>18.10 ± 10.71</td>
<td>–</td>
</tr>
<tr>
<td>SAPS, Total Score</td>
<td>–</td>
<td>7.45 ± 12.00</td>
<td>–</td>
</tr>
<tr>
<td>CPZ Equivalents</td>
<td>–</td>
<td>244.22 ± 161.22</td>
<td>–</td>
</tr>
</tbody>
</table>

Values are presented as mean ± SD or %.

BPRS, Brief Psychiatric Rating Scale; CPZ, chlorpromazine; SANS, Scale for the Assessment of Negative Symptoms; SAPS, Scale for the Assessment of Positive Symptoms.

*alpha < 0.0001.
functionally defined by MacDonald et al. (26). After placing ROIs in standard space, they were transformed into native space prior to statistical analysis as described above.

We also performed an exploratory searchlight whole-brain RSA using 400 parcellations acquired from Schaefer et al. (27). As was done previously, parcellations were transformed into native space prior to statistical analyses (familywise error corrected at $p < .05$).

Representational Similarity Analysis. RSA is a multi-variate approach correlating patterns of voxel activation across objects that share a similar feature of interest to determine if brain regions are sensitive to that feature (28,29). For example, imagine an area of the brain encoding representations of dogs. Patterns of activation in that area for one dog will be similar to patterns of activation for another dog. In contrast, patterns of activation for a cat in that area might show shared activation across some voxels because of some shared features (e.g., 4 legs, domestic animal), but the overall pattern of activation for the cat will be more dissimilar than either of the dog representations, confirming that the area is most sensitive to processing dog-related representations. For this study, we used RSA to understand how the DLPFC and posterior hippocampus represented fixed versus random sequences.

To do this, we first assessed patterns of activity across voxels within the DLPFC and posterior hippocampus during single trials using parameter estimates (i.e., beta weights) for each object, estimated through the least-square2 method (30). A general linear model computed beta weight estimates for each object. For each functional run, there were 75 general linear models (5 objects/sequence $\times$ 5 sequences $\times$ 3 repetitions) for a total of 300 beta maps (4 runs $\times$ 75 beta maps/run). Outlier beta maps, determined by a signal intensity lying in 1% of all beta maps, were excluded from analyses.

Next, we examined voxel pattern similarity for fixed and random sequences by calculating Pearson’s correlation coefficient between beta weight vectors for pairs of trials, which were Fisher transformed and averaged in 3 ways (Figure 1). To examine fixed sequence representations, an average was taken for all fixed sequences across repetitions and runs, where each object was in the same position. For random sequences, an average was taken across all random sequences, where the position of objects varied. To include representations where object information was shared between objects in different sequences regardless of position, voxel patterns were rearranged within random sequences and averaged. These 2 averages were combined to create a full picture of random sequence representation. For the bilateral DLPFC, we performed a three-way ANOVA to identify effects of group (HC vs. SZ), hemisphere (left vs. right), and sequence representation (fixed vs. random). Based on prior research using a similar paradigm (24), we limited analyses of the posterior hippocampus to the right hemisphere. We performed a two-way ANOVA in the right posterior hippocampus examining effects of group (HC vs. SZ) and sequence representation (fixed vs. random). Correlation analyses were performed to determine associations between RT sequence prediction effects and similarity values (fixed vs. random) gleaned from RSA results.

RESULTS

Behavioral Results

Based upon previous results (3), we hypothesized that people with SZ would show reduced sequence prediction effects. This was supported by an ANOVA, which revealed main effects of group ($F_{1,83} = 8.27, p = .005$) and sequence type ($F_{1,83} = 21.90, p < .001$), as well as a significant group by sequence interaction ($F_{1,83} = 8.93, p = .004$). As shown in Figure 2, t tests investigating sequence prediction effects (fixed versus random RT for objects 2–5) revealed that this interaction was due to HC subjects showing a greater speeding of RT for fixed versus random sequences than people with SZ ($t_{83} = −2.99, p = .004$). Thus, although people with SZ were able to learn and retrieve well-learned sequences and speed their RTs, these memory prediction effects were reduced relative to HC subjects (Figure S1 illustrates the difference between objects within each sequence).

fMRI Results

Based on previous work (24), we hypothesized that the DLPFC and posterior hippocampus would be involved in supporting memory-based prediction for objects within a temporal context and that these representations would be reduced in people with SZ. We examined this separately for the DLPFC and hippocampus using RSA to compare voxel pattern similarities for fixed and random sequences.

Supporting our hypothesis for the DLPFC, an ANOVA revealed a main effect of sequence, with fixed sequences showing higher similarity than random sequences ($F_{1,83} = 14.84, p < .001$) (Figure 3). There was no main effect of hemisphere ($F_{1,83} = 3.37, p = .07$). Although there was no main effect of group, there was an interaction between sequence and group ($F_{1,83} = 5.67, p = .02$). Post hoc tests revealed that in HC subjects only, DLPFC voxel pattern similarity was higher for fixed sequences than for random sequences ($t = 5.16, p < .001$). Conversely, in the SZ sample, there were no differences in how the DLPFC represented objects in fixed versus random sequences ($t = 0.92, p = .36$). These data suggest that DLPFC dysfunction may be associated with memory-based prediction deficits in individuals with SZ.

In the posterior hippocampus, an ANOVA revealed no main effects of group or sequence. There was, however, a trend toward an interaction between group and sequence ($F_{1,87} = 3.20, p = .08$) (Figure 3). Exploratory post hoc analyses revealed that this trend-level interaction was due to increased pattern similarity for fixed versus random sequences in the right posterior hippocampus of HC subjects ($t = 2.26, p = .03$) but not in people with SZ ($t = −0.55, p = .58$). Results did not support our hypothesis that hippocampal dysfunction contributes to temporal sequence memory deficits in SZ.

Searchlight analyses did not reveal other areas showing increased pattern similarity for fixed versus random sequences. Thus, there were no effects in other parts of the brain.

Association With Performance. To determine relationships between sequence prediction effects and representational similarity, we performed correlation analyses (Figure 4).
In the left DLPFC, sequence similarity representations (fixed-random) were significantly correlated with sequence prediction effects (fixed-random) in HC subjects \( (r = -0.27, p = .047) \) but not in individuals with SZ \( (r = -0.18, p = .33) \). In the right DLPFC, there was no correlation between sequence prediction and representational similarity. These data suggest that as sequence prediction increases (indicated by an increasingly negative value), representational similarity increases in the left DLPFC. Although this correlation was only significant in HC subjects, a regression analysis (Supplement) did not reveal a significant interaction. Thus, there were no significant group differences in the strength of the relationship between DLPFC similarity and sequence prediction.

Analyses were also performed for the bilateral posterior hippocampus, which did not reveal any significant results. Pattern similarity in the posterior hippocampus, therefore, did not appear to be associated with sequence prediction effects.

Association With Clinical Symptoms. Correlational analyses did not reveal any significant relationships between DLPFC pattern similarity effects and severity of clinical symptoms (total scores for Scale for the Assessment of Negative Symptoms, Scale for the Assessment of Positive Symptoms, and Brief Psychiatric Rating Scale) in the SZ sample (all \( r \) values \( > 0.08 \)).

DISCUSSION

We rely on memory to make accurate predictions about our changing environment. In this study, we investigated whether people with SZ showed deficits in memory-based prediction using a temporal sequence paradigm \((2,3,31)\). Although both groups predicted and responded more quickly to objects within a previously learned sequence (i.e., faster RTs for fixed vs. random sequences), this effect was reduced in people with SZ.

Figure 2. Sequence prediction indicated by the difference in reaction times for objects 2–6 between fixed and random sequences. Reaction time for fixed sequences was faster than random sequences for both groups, with healthy control (HC) subjects showing a significantly greater difference. Error bars indicate the standard error of the mean. SZ, schizophrenia.

Figure 3. (A, B) In the left (A) and right (B) dorsolateral prefrontal cortex (DLPFC), healthy control (HC) subjects showed significantly greater similarity for fixed sequences compared with random while individuals with schizophrenia (SZ) did not. (C) The left posterior hippocampus showed no group or sequence differences. (D) In the right posterior hippocampus, in HC subjects only, fixed sequences showed significantly greater similarity compared with random sequences. Error bars indicate the standard error of the mean.
Memory-Based Predictions in Schizophrenia

SZ relative to HC subjects. Multivariate analyses of fMRI data revealed that participants with SZ showed disrupted neural representations of learned sequences in the DLPFC. These findings support the conclusion that people with SZ can learn temporal sequences, but their ability to use this sequence memory to predict future events is dysfunctional.

Sequence prediction effects were measured indirectly as individuals responded to objects contained in sequences that could be learned (i.e., fixed) or could not be learned (i.e., random), with speeding of semantic decisions for learned versus unlearned sequences providing evidence of successful prediction. Behavioral results indicate that individuals with SZ were capable of forming and using memories to predict the next object in the sequence and, thereby, guide their behavior. As shown previously (3), both groups showed evidence of sequence learning, but memory prediction effects were reduced in people with SZ relative to HC subjects. Therefore, memory impairments do not appear due to a lack of attention or a generalized memory deficit. However, individuals with SZ did not improve predictions to the same degree as HC subjects, suggesting that people with SZ were less successful in using memory representations to guide predictions (14).

Although semantic priming deficits have been reported in SZ (32,33), it is notable that, in this study, objects in learned and random sequences were equally familiar. Thus, differential effects of sequence learning on semantic decisions between patients and control subjects cannot be explained by differences in semantic priming. Instead, our results are more consistent with the idea that people with SZ have a reduced ability to use sequential regularities to predict upcoming events.

To better understand these memory-related prediction impairments, we used RSA to characterize representations of information from temporal sequences in the DLPFC and posterior hippocampus. Multivariate analyses revealed that, in HC subjects, representational similarity was higher across repetitions of objects in learned sequences relative to repetitions of objects in random sequences in the DLPFC. These effects were not significant for people with SZ, and DLPFC voxel pattern similarity differences between objects in learned and random sequences were significantly higher in HC subjects than in people with SZ. Moreover, the fidelity of DLPFC representations of objects in learned sequences was predictive of sequence prediction success in HC subjects only, although there were no significant group differences in the size of the association. Results are consistent with a large body of behavioral, eye-tracking, EEG, and fMRI research linking both memory (25,34) and prediction (23) impairments to DLPFC dysfunction in people with SZ. Impaired DLPFC control of memory encoding and retrieval has been repeatedly demonstrated in people with SZ on both an individual study (31,34) and meta-analytic level (25).

In addition to the DLPFC, numerous studies supported the idea that hippocampal abnormalities might contribute to relational memory deficits in SZ (35). Several studies documented reductions in hippocampal volume in individuals with SZ (36), and others (37–39), including results from our group (31,40), demonstrated reduced hippocampal activation during relational memory retrieval in people with SZ relative to HC subjects. In this study, however, we did not observe any evidence for hippocampal dysfunction in people with SZ. Exploratory analyses of data restricted to the HC group revealed that, consistent with our previous study (24), pattern similarity in the right posterior hippocampus was higher for objects in learned relative to random sequences. Although these effects were not significant in people with SZ, we did not observe any significant between-group differences in hippocampal sequence representations, nor did we find significant relationships between hippocampal results and sequence prediction effects in either group. Thus, results did not support the hypothesis that sequence-based prediction deficits in people with SZ were related to impaired hippocampal function.

As described in Zheng et al. (3), people with SZ learned sequences more slowly than HC subjects, consistent with a deficit in relational memory. As published previously (2,41), participants were highly trained on fixed and random sequences prior to scanning, thus enabling people with SZ to
compensate for any learning deficits. During scanning, partici-
pants were not asked to explicitly recall sequences, so we
would only expect them to show faster decisions for objects in
fixed sequences if they proactively used memory for the
learned sequences to accurately predict upcoming objects.
Thus, results are consistent with concluding that even when
learning is sufficient to overcome relational memory deficits,
people with SZ are impaired using what was learned to predict
upcoming events, with this deficit strongly associated with
DLPFC dysfunction.

A challenge of studying people with SZ is the heterogeneity
of the disorder, which can increase variability, and potential
medication effects and differences in clinical presentations.
One might expect that we would have found correlations with
positive symptoms given literature linking predictive coding
deficits with severity of positive symptoms (18). One notable
difference between our study and previous work is that par-
ticipants in this study were patients with early psychosis who
were clinically stable with mild to moderate symptoms.
Therefore, a restricted range may have contributed to lack of
clinical correlations. Most participants in the SZ group were
receiving second-generation antipsychotics, and when analy-
ses were repeated after excluding unmedicated participants,
there was no difference in the pattern of behavioral or fMRI
results. We also did not find any significant correlations with
standardized medication dose (i.e., chlorpromazine equiva-
lents). Thus, results do not appear to be influenced by medi-
cation or symptom severity effects. We did experience
significant data loss due to excess motion and operator error.
This was likely related to both operator and participant fatigue
because fMRI recordings were obtained immediately following
a priori regions in the hippocampus and prefrontal cortex
based upon previous fMRI studies (2,31), raising the possibility
that there were task effects or group differences within other
regions of the brain. To address this, we conducted an
exploratory whole-brain searchlight analysis, which did not
reveal any task effects or group differences in other brain
regions.

In conclusion, results indicate a key finding: Individuals with
SZ were able to learn sequences, but there was dysfunction in
using prior knowledge about sequences to aid in prediction of
upcoming objects. HC subjects were more successful than
people with SZ in engaging their DLPFC to form object/ 
sequence representations to facilitate prediction of upcoming
objects in learned sequences. These findings support prior
theories proposing that there are aberrant prediction pro-
cesses in people with SZ (14,17). Ongoing efforts to remediate
memory-based prediction deficits in SZ using neuro-
stimulation, pharmacology, or behavioral interventions may be
most successful if they target DLPFC-related control
processes.

ACKNOWLEDGMENTS AND DISCLOSURES
This research was supported by funding from the National Institute of
Mental Health (Grant No. R01MH105411 [to JDR and CR]).

We thank both the participants from the early psychosis program and the
healthy volunteers who participated in this study.

The authors report no biomedical financial interests or potential conflicts of
interest.

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Memory-Based Predictions in Schizophrenia