Recent neuroimaging studies have reported deficits in functional integration between prefrontal cortex and the hippocampal formation in schizophrenia. It is unclear whether these alterations are a consequence of chronic illness or its treatment, and whether they are also evident in non-psychotic subjects at increased risk of the disorder. We addressed these issues by investigating prefrontal–hippocampal interactions in patients with first episode schizophrenia and subjects with an At Risk Mental State (ARMS). Using functional Magnetic Resonance Imaging, we measured brain responses from 16 individuals with an ARMS, 10 patients with first episode schizophrenia and 14 healthy controls during a delayed matching to sample task. Dynamic causal modelling was used to estimate the effective connectivity between prefrontal cortex and anterior and posterior hippocampal regions. The normal pattern of effective connectivity from the right posterior hippocampus to the right inferior frontal gyrus was significantly decreased in both first episode patients and subjects with an ARMS (ANOVA; F = 8.16, P = 0.01). Interactions between the inferior frontal gyrus and the anterior part of the hippocampus did not differ across the three groups. Perturbed hippocampal–prefrontal interactions are evident in individuals at high risk of developing psychosis and in patients who have just developed schizophrenia. This suggests that it may be a correlate of increased vulnerability to psychosis and that it is not attributable to an effect of chronic illness or its treatment.
Introduction

Neuropathological (Arnold and Trojanowski, 1996; Harrison and Eastwood, 2001), structural (Borgets, 1990) and functional (Carter et al., 1999; Heckers et al., 1998) neuroimaging studies provide converging evidence for localized anatomical and functional abnormalities in both the prefrontal cortex and hippocampal formation in schizophrenia. In addition, cognitive models of schizophrenia propose that a disturbance of the normal interaction between these two regions might underlie many of the associated symptoms and cognitive deficits (Weinberger et al., 1992; Fletcher, 1998). Consistent with this notion, several neuroimaging studies have reported altered functional integration between prefrontal and hippocampal regions in schizophrenia (Weinberger et al., 1992; Heckers et al., 1999; Meyer-Lindenberg et al., 2005; Zhou et al., 2007, 2008). For instance, Meyer-Lindenberg and colleagues (2005) reported a regionally specific alteration in the functional coupling between the dorsolateral prefrontal cortex and hippocampal formation in the context of a working memory task (Meyer-Lindenberg et al., 2005), while reduced functional connectivity between the medial prefrontal cortex and the hippocampi has been described in patients studied in the resting state (Zhou et al., 2008).

As these studies have largely been conducted in patients with chronic schizophrenia, the extent to which alterations in functional integration between regions are secondary to psychotic illness or its treatment is unclear. Some neuroimaging abnormalities in schizophrenia appear to change progressively over the course of the disorder, although to date these data have mainly been derived from volumetric rather than functional studies (Lieberman, 1999; Lieberman et al., 2001; Cahn et al., 2006). There is also evidence that antipsychotic treatment can alter both the structure and function of cortical and subcortical regions (for a review see Scher and Falkai, 2006). The influence of these potential confounds may be reduced by studying patients at the onset of schizophrenia, who have had minimal exposure to treatment. A second issue is whether alterations in functional integration between regions are specific to schizophrenia or are also evident in individuals at high risk of the disorder. Individuals with an At Risk Mental State (ARMS) have a 25–40% risk of developing a psychotic disorder in the next 24 months (Miller et al., 2003; Yung et al., 2003; Mason et al., 2004). Structural and functional imaging studies have revealed that the ARMS is associated with regional volumetric and functional abnormalities that are qualitatively similar to those in patients with schizophrenia but are less severe (Phillips et al., 2002; Pantelis et al., 2003; Morey et al., 2005; Borgwardt et al., 2007; Broome et al., 2009). In particular, these studies indicate that the prefrontal cortex and the hippocampal region are affected, as in schizophrenia. However, to our knowledge, the functional relationship between these regions has yet to be investigated in the ARMS, or in other high-risk groups.

The first aim of the present study was to examine prefronto-hippocampal connectivity in patients with first episode schizophrenia and individuals with an ARMS. We used functional MRI (fMRI) to measure brain responses while subjects performed a delayed matching to sample (DMTS) task which engages both the prefrontal cortex and hippocampal region (Picchioni et al., 2007). We then used dynamic causal modelling (Friston et al., 2003; Mechelli et al., 2003) to estimate the influence that these regions exerted on each other (Friston et al., 1993b). Effective connectivity is distinct from functional connectivity, which reflects temporal correlations between activation in different regions (Friston et al., 1993a) without providing information about the direction of influence between them. Our principal hypothesis, based on evidence of prefrontal and hippocampal abnormalities in both patients with schizophrenia and subjects at high risk of psychosis, was that alterations in prefronto-hippocampal connectivity would be evident in both patients with first episode schizophrenia and subjects with an ARMS.

The hippocampal formation is structurally and functionally heterogeneous. Its anterior and posterior parts have different afferent and efferent connections and are implicated in different cognitive functions. With respect to the anatomical prefronto-hippocampal connectivity, comparative studies have shown that the rostral CA1’ and CA1 fields of the hippocampal formation project directly to medial prefrontal cortices while lateral prefrontal areas receive indirect projections from the caudal subicular and presubicular fields through the fornix via the entorhinal cortex (Gaffan, 1974; Ferino et al., 1987; Barbas and Blatt, 1995). Although most of these indirect projections are ipsilateral, some appear to cross in the body of the fornix (Carr and Sesack 1996; Kuroki et al., 2006). With respect to prefrontal projections to the hippocampal region, the hippocampus appears to receive projections only indirectly from the ipsilateral medial prefrontal cortex through the thalamic nucleus reuniens, whereas lateral prefrontal cortices project mainly to the posterior parahippocampal region (Roberts et al., 2006; Vertes et al., 2007). Functional neuroimaging studies of memory processing have found that anterior hippocampal regions are preferentially involved in encoding, while posterior hippocampal regions show familiarity effects and seem to be more involved in retrieval (Maguire et al., 1996; Lepage et al., 1998; Schacter and Wagner, 1999; Strange and Dolan, 1999). However, most structural and functional studies of hippocampal abnormalities in schizophrenia have not distinguished between the anterior and posterior parts of hippocampus (Wright et al., 2000; Meyer-Lindenberg et al., 2005; Glahn et al., 2008). A secondary aim of the present study was to assess whether the connectivity of the hippocampal region would vary between its putative functional subdivisions. We therefore examined the effective connectivity of the anterior and posterior portions of the hippocampus separately.

Materials and Methods

Participants

The study was approved by the Institute of Psychiatry Ethical Committee. All subjects gave written informed consent after a full description of the study aims and design.
**ARMS group (n = 16)**

Individuals meeting the Personal Assessment and Crisis Evaluation (PACE) criteria for the ARMS (Yung et al., 1998) were recruited from Outreach and Support in South London (OASIS). Individuals met the criteria for the ARMS if they presented with one or more of the following: (i) ‘attenuated’ positive symptoms; (ii) a brief psychotic episode of <1 week duration and that resolves without antipsychotic medication; or (iii) either they have a first degree relative with psychosis or they have a personal history of schizotypal personality disorder. Any of these traits factors have to be coupled with a recent decline in social and occupational functioning. The diagnosis was based on assessment by two experienced clinicians using the Comprehensive Assessment for the ARMS (CAARMS; Yung et al., 2003). All the participants were right-handed and none of them had ever received antipsychotic medication.

**First Episode group (n = 10)**

Patients who had recently presented with a first episode of psychosis were recruited from Lambeth Early Onset (LEO) Services (http://www.slam.nhs.uk/services/). All met ICD-10 criteria (WHO, 1992) for a schizophrenia or psychosis at the time of scanning and met OPCRIT criteria (McGuffin et al., 1991) for schizophrenia when subsequently reassessed 12 months after first presentation. Three patients were medication naive. The other seven had been treated with either oral risperidone or quetiapine for a mean of 15 days (95% CI 11.6–18.4) at chlorpromazine equivalent mean dose of 121 mg/day. All the patients included in this study were right-handed.

**Controls (n = 14)**

Healthy volunteers without any current or lifetime evidence of psychiatric disorder were recruited by advertisement from the local community. All healthy participants were right-handed.

General Intellectual function was estimated using the National Adult Reading Test (NART). The severity of symptoms in the clinical groups on the day of scanning was assessed with the Positive and Negative Symptom Scales (PANSS) (Kay et al., 1987) by a psychiatrist trained in its use. The groups were matched on socio-demographic variables (Table 1) and subjects were excluded if there was a history of neurological disorder or if they met (DSM-IV) criteria for a substance misuse disorder.

**Neuroimaging experiment**

The cognitive task we employed has been detailed elsewhere (Picchioni et al., 2007). In brief, fMRI data were acquired while subjects performed a modified version of the DMTS test from the Cambridge Neuropsychological Test Automated Battery (CANTAB). During the first ‘encoding’ phase, subjects were presented with a complex abstract pattern (the sample) for 5000 ms in the centre of the screen and instructed to remember it, as they would be asked to identify it later. The following ‘maintenance’ phase involved a delay during which subjects had to hold the sample in memory while maintaining visual fixation on a central cross. In the final ‘recognition’ phase, subjects were shown four patterns in a North, South, East and West distribution around a central location for 6000 ms and asked to identify the original sample via a joystick press in the corresponding direction. The duration of the maintenance delay varied across trials, resulting in three maintenance conditions: simultaneous, 4000 and 12 000 ms. Simultaneous trials involved no delay; here the sample and choice patterns were shown together at recognition. In the other trials, there was a delay of either 4000 or 12 000 ms between encoding and recognition; here only the choice patterns were displayed at recognition. At the end of each trial subjects were asked to maintain visual fixation on a central cross in order to equalize the inter-trial (encoding) interval to 27 000 ms while randomly varying the inter-stimulus (recognition) interval.

**Data acquisition**

The imaging procedures have been detailed elsewhere (Picchioni et al., 2007). In brief, images were acquired in a 1.5 T system (Signa LX-GE, Milwaukee, USA) at the Maudsley Hospital with TR of 2 s, TE 40 ms, slice thickness 7 mm and interslice gap of 0.7 mm. A total of 648 images volumes were acquired in two runs of 10 min, with each whole brain volume consisting of 22 near-axial slices parallel to the intercommissural (AC-PC) line. The first four images were discarded to allow the magnetization to reach equilibrium amplitude.

**Data analysis**

Pre-processing

Pre-processing of the functional volumes was performed using SPM5 (http://www.fil.ion.ucl.ac.uk/spm), running in Matlab 6.5 (Mathworks Inc. Sherbon MA, USA). All volumes from each subject were realigned using the first as reference and resliced with sinc interpolation. The functional images were spatially normalized using Friston et al., 1995a, b to a standard MNI-305 template using non-linear-basis functions. Functional data were spatially smoothed with a 6-mm full width at half maximum isotropic Gaussian kernel, to compensate for residual variability in functional anatomy after spatial normalization and variability in functional anatomy after spatial normalization.

**Table 1** Demographics and clinical characteristics of the three experimental groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Controls, n = 14</th>
<th>ARMS, n = 16</th>
<th>First episode, n = 10</th>
<th>Group comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>26.04 (4.64)</td>
<td>24.13 (3.97)</td>
<td>25.50 (5.89)</td>
<td>$F = 0.65, P = 0.53$</td>
</tr>
<tr>
<td>N, Male/Female</td>
<td>9/5</td>
<td>10/6</td>
<td>7/3</td>
<td>$\chi^2 = 0.16, df = 2, P = 0.92$</td>
</tr>
<tr>
<td>Premorbid IQ (NART)</td>
<td>114.0 (8.6)</td>
<td>100.3 (11.8)</td>
<td>105.4 (10.5)</td>
<td>$F = 6.75, P = 0.003$</td>
</tr>
<tr>
<td>PANSS Total</td>
<td>NA</td>
<td>44.2 (10.9)</td>
<td>58.1 (9.5)</td>
<td>$F = 9.43, P = 0.058$</td>
</tr>
<tr>
<td>PANSS Positive</td>
<td>NA</td>
<td>11.3 (3.6)</td>
<td>18.5 (4.6)</td>
<td>$F = 20.48, P &lt; 0.001$</td>
</tr>
<tr>
<td>PANSS Negative</td>
<td>NA</td>
<td>9.3 (2.3)</td>
<td>10.0 (2.3)</td>
<td>$F = 0.21, P = 0.65$</td>
</tr>
<tr>
<td>Typical: Atypical</td>
<td>NA</td>
<td>NA</td>
<td>0.7 (3 NA)</td>
<td>NA</td>
</tr>
<tr>
<td>CPZ equivalents</td>
<td>NA</td>
<td>NA</td>
<td>121.43 (26.73)</td>
<td>NA</td>
</tr>
</tbody>
</table>

Data reflect mean (SD) unless otherwise stated.

CPZ = chlorpromazine; NA = not applicable.
to permit application of Gaussian random field theory for adjusted statistical inference.

**Statistical parametric mapping**

We performed a standard statistical analysis of regional responses to identify regional activations in each subject independently. To remove low-frequency drifts, the data were high-pass filtered using a set of discrete cosine basis functions with a cut off period of 128 s. Each of the five conditions (i.e. encoding; 0 ms maintenance; 4000 ms maintenance; 12 000 ms maintenance; recognition) was modelled independently by convolving the onset times with a canonical haemodynamic response function. In addition, incorrect responses were modelled separately in each subject and then excluded from the second level analysis. The parameter estimates were calculated for all brain voxels using the general linear model and contrasts were computed for each experimental condition. The subject-specific contrast images were then entered into a second level ANOVA to make inferences at the second level (Penny and Holmes, 2004). This allowed us to identify areas of the prefrontal cortex that expressed differential activation across the first episode, ARMS and control groups during task performance relative to fixation. These prefrontal areas were then entered into our dynamic causal modelling (DCM) analysis in order to test the hypothesis that abnormal prefrontal function was associated with altered functional integration with anterior and posterior hippocampal regions.

**Dynamic casual modelling**

We used DCM (Friston *et al.*, 2003; Mechelli *et al.*, 2003) as implemented in SPM5 software. The aim of dynamic causal modelling is to estimate, and make inferences about, the influence that one neural system exerts over another and how this is affected by the experimental context. In dynamic causal modelling, a reasonably realistic but simple neuronal model of interacting neural regions is constructed. Dynamic causal modelling uses a previously validated biophysical model of fMRI measurements to predict the underlying neuronal activity from the observed haemodynamic response (Friston *et al.*, 2000). The estimated underlying neural responses are then used to derive the connectivity parameters, as described elsewhere (Friston *et al.*, 2003; Mechelli *et al.*, 2003). In order to test whether the interaction between prefrontal cortex and anterior or posterior hippocampal regions is disturbed in first episode schizophrenia and in the ARMS, for each subject four dynamic causal models were constructed (Fig. 1). Each model included two areas: an inferior frontal region and an anterior or posterior hippocampal region. The inferior frontal region [mean coordinates (x, y, z): −32, 22, 6 (left); (x, y, z): 32, 22, 6 (right)] was selected on the basis that it showed increased activation in the first episode group relative to healthy controls during recognition relative to fixation in the standard SPM analysis. The coordinates of the anterior and posterior hippocampal regions were derived from previous two voxel-based morphometry studies (Maguire *et al.*, 2000, 2003) of grey matter volume, which provided evidence suggesting a functional segregation within the hippocampus and from [left anterior hippocampus (x, y, z): −30, −10, −20; left posterior hippocampus (x, y, z): −30, −10, −20; right anterior hippocampus (x, y, z): 30, −10, −20; right posterior hippocampus (x, y, z): 30, −30, −10]. The first dynamic causal modelling model (Fig. 1A) included the left inferior frontal region and the left anterior hippocampus and allowed us to test whether abnormal prefrontal function in the left hemisphere was associated with abnormal functional integration with the anterior hippocampus of the same hemisphere. The second dynamic causal modelling model (Fig. 1B) included the left inferior frontal region and the left posterior hippocampus; this model allowed us to test whether abnormal left prefrontal function could be explained by abnormal functional integration with the posterior part of the left hippocampus. The third (Fig. 1C) and fourth (Fig. 1D) models were identical to the first two except that the inferior frontal and the hippocampal regions were localized to the right instead of the left hemisphere. Principal eigen variates were extracted to summarize regional responses in 9 mm spheres centred on the regions included in the dynamic causal modelling models. To account for individual differences, the location of these regions was based upon the local maxima of the subject-specific statistical parametric maps, defined as the nearest maxima (within 4 mm) of the group maxima. The network comprised forward and backward connections (i.e. endogenous

![Figure 1](image_url)

**Figure 1** Four dynamic casual models that were used to investigate the regional prefrontal–hippocampal coupling in first episode, ARMS and control groups. Each model included a prefrontal region and the ipsilateral anterior or posterior hippocampal region. LIFG = left inferior frontal gyrus; LAH = left anterior hippocampus; LPH = left posterior hippocampus; RIFG = right inferior frontal gyrus; RAH = right anterior hippocampus; RPH = right posterior hippocampus. The solid arrow in (D) indicates that there was significant decreased right-sided effective connectivity between the RPH and the RIFG, irrespective of the maintenance delay during the task in FE patients and ARMS subjects relative to controls (statistical threshold of $P=0.01$).
connections) characterizing the coupling between prefrontal and hippocampal regions throughout the whole experiment, regardless of different components of the task (i.e. encoding, maintenance and recognition; Fig. 1). The stimulus function, which encoded the presentation of the sample, its maintenance and its recognition at each of the three maintenance delays, entered the dynamic causal model through the hippocampal region. The resulting perturbation was then allowed to propagate throughout the model via the interconnections between hippocampal and prefrontal regions.

The forward and backward ‘endogenous connections’ were estimated for each subject independently. In dynamic causal modelling, the parameters describe the rate of change (units of 1/s) in the ‘target’ region as a linear function of the activity in the ‘source’ region. Positive (or negative) intrinsic connection strengths indicate that the rate of change (i.e. an increase in activity) in the target region is positively (or negatively) proportional with activity in the source region.

The subject-specific estimates were then entered into an ANOVA in SPSS in order to identify significant differences amongst the three experimental groups. Our four dynamic causal models resulted in a total of eight intrinsic connection comparisons. A Bonferroni correction for multiple comparisons would have resulted in a corrected threshold of \( P \leq 0.006 \) (0.05/8). However, this correction would have been inappropriate since it assumes comparisons to be independent, whereas statistical inferences about intrinsic connections are likely to be highly correlated. In the absence of any established procedure, as in previous dynamic causal modelling studies (Mechelli et al., 2007), we controlled for false positive rate using a relatively conservative statistical threshold of \( P < 0.025 \), which yields an expected false positive rate of 2.5%. Once significant differences amongst the three experimental groups were identified using the ANOVA, post hoc two-tailed \( t \)-tests in SPSS (SPSS version 13.0, Chicago) were used to better characterize the intrinsic endogenous.

## Results

### Behavioural data

The proportion of correct responses and the response latencies are displayed in Table 2.

### Correct responses

There was a trend for a significant interaction between group and delay maintenance (\( \chi^2 = 9.26, \ df = 4, \ P = 0.055 \)). A series of pair-wise \( t \)-tests revealed that in the First Episode group the proportion of correct responses was significantly lower than in the control group at any maintenance condition. Although in the ARMS group the proportion of correct responses was lower than in the control group, the difference did not reach statistical significance (Table 2).

### fMRI

Encoding was associated with greater, bilateral activation across the three groups in the superior parietal gyrus extending through the intraparietal sulcus to the supramarginal gyrus (BA7 & BA40), the inferior and middle occipital gyrus (BA18), the middle extending to the superior frontal gyrus (BA6/8), the insula and the anterior cingulate. Repeated measures ANOVA did not reveal a significant interaction between group and encoding (Fig. 2).

The main effect of maintenance across groups was associated with greater bilateral activation in the anterior part of the insula (BA13), the superior parietal gyrus extending to the inferior (BA7/40), and the superior frontal gyrus (BA6). A greater activation was also observed in the left dorsal precentral gyrus and the right anterior cingulate. No significant interaction was found between group and maintenance (Fig. 2).

Increased BOLD response at correct recognition common to the three maintenance delays (0, 4000 and 12 000 mm) across the three groups compared with rest was associated with right-sided activation in the inferior frontal gyrus and insula, and bilateral activation in the middle frontal gyrus, superior parietal lobule, precuneus, cuneus, inferior occipital gyrus and cerebellar cortex (\( P < 0.05 \), FEW corrected; Fig. 2).

Analysis of the group \( \times \) recognition task interaction (Fig. 3) showed significant differences in the inferior frontal gyrus and the superior temporal gyrus bilaterally, as well as in the right insula and middle temporal gyrus. In all these areas, first episode patients showed greater activation than both the control and ARMS groups (Fig. 3).

### Table 2 Performance data during DMTS task by groups

<table>
<thead>
<tr>
<th>Mnemonic delay</th>
<th>Group</th>
<th>First episode psychosis</th>
<th>ARMS</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proportion correct responses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simultaneous</td>
<td>0.79 (( P = 0.018 ))</td>
<td>0.92</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>0.71 (( P = 0.021 ))</td>
<td>0.77</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>12 000</td>
<td>0.64 (( P = 0.010 ))</td>
<td>0.71</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>
| Response latency (s) for correct responses Mean (SD)
| Simultaneous  | 2.38 (1.34)                  | 2.24 (0.98)             | 2.32 (1.02) |
| 4000          | 2.30 (1.30)                  | 2.48 (1.24)             | 2.50 (1.12) |
| 12 000        | 2.47 (1.54)                  | 2.65 (1.31)             | 2.66 (1.16) |

Data reflect mean (SD). We report the \( P \)-values of the FE and Control groups differences (in brackets) with the significantly lower proportions of correct responses in FE highlighted in bold.
Figure 2  Main effect of encoding, maintenance and recognition tasks showing regions with significant activations across the three groups. Highlighted voxels are significant at $P \leq 0.05$, FWE corrected.

Figure 3  (Upper left and middle) Group × task interaction. In regions shown in yellow, activation in First Episode patients was significantly greater than in both Control and ARMS subjects ($P \leq 0.05$ FWE corrected). (Upper right) Render cut-out showing the left Inferior Frontal Gyrus (IFG), where the interaction was most significant. The parameter estimates in the IFG in the three groups are shown below. Error bars indicate 90% CI.


Dynamic casual modelling: endogenous connections

Based on the fMRI results, we constructed four DCM models estimating the functional coupling between inferior frontal and hippocampal regions in the left and right hemispheres (Fig. 1). We were interested in the strength of the endogenous connections which refer to the impact that one region exerted over another (regardless of the length of the maintenance delay) during the task.

When all subjects were combined, the forward and backward endogenous connections between the posterior hippocampus and the inferior frontal cortex were significantly greater than zero, indicating strong functional integration during task performance (Table 3). Group comparisons revealed that the intrinsic connection from right posterior hippocampus to the right inferior frontal gyrus differed across the three groups (ANOVA; \( F = 8.16, \text{df} = 2, \ P = 0.01 \)). Post hoc, two-tailed \( t \)-tests showed that this connection was stronger in controls than both first episode patients (two-sample \( t \)-test; \( P = 0.007 \)) and ARMS subjects (two-sample \( t \)-test; \( P = 0.004 \)), but did not differ between with the first episode and ARMS groups (Table 3 and Fig. 1D). The parameters for the reverse connection from the right inferior frontal gyrus to the posterior hippocampus, the connections between the right inferior frontal gyrus and the anterior hippocampus, and the connections between the left inferior frontal gyrus and both the anterior and posterior hippocampus did not differ significantly between the groups, even at a liberal statistical threshold (ANOVA; \( P > 0.1 \)).

During correct recognition, first episode patients expressed significantly increased activation in the inferior frontal gyrus bilaterally, relative to both controls and individuals with an ARMS. However, there was no significant difference in activation between individuals with an ARMS and healthy controls in this region. Functional neuroimaging studies of working memory in individuals with psychosis have repeatedly reported both reduced and increased engagement of neuronal resources within the prefrontal cortex (Callicot et al., 2000; Perlstein et al., 2001; Glhan et al., 2005). One possible explanation for this inconsistency is that there may be a difference in the relationship between prefrontal activation and working memory capacity and behavioural performance (Manoach et al., 2003; Bertolino et al., 2006). In our study, the increased activation in the inferior frontal gyrus in first episode patients may be interpreted as reflecting ‘inefficient’ cortical function and support the hypothesis of compromised neural strategies for handling information, as proposed when this has previously been observed in the context of other working memory tasks in schizophrenia (Callicot et al., 2003). The possibility that this increased activation was related to an effect of antipsychotic medication cannot be excluded either (Mendrek et al., 2005; Tan et al., 2005; Fusar-Poli et al., 2007), although the first episode patients we studied had only briefly been exposed to low doses of medication. Further, and more speculatively, increased prefrontal activation during this WM task could be in part related to the genetic modulation of dopamine in patients with schizophrenia (Egan et al., 2001; Matsumoto et al., 2003; Bertolino et al., 2004; Bertolino et al., 2006a, b).

The focus of the present investigation was to examine functional integration between this inferior frontal region and the anterior and posterior segments of the hippocampal formation. Interestingly, the bilateral anterior and posterior regions of the hippocampus did not show strong regional activation in the standard SPM analysis and yet the posterior regions expressed strong functional integration with the inferior prefrontal cortex, as revealed by our dynamic casual modelling analysis. This dissociation illustrates that inferences about functional integration

### Table 3 Endogenous connections in controls, ‘ARMS’ and first episode

<table>
<thead>
<tr>
<th>Endogenous connections</th>
<th>Controls, ( n = 14 )</th>
<th>ARMS, ( n = 16 )</th>
<th>First episode, ( n = 10 )</th>
<th>All groups combined (( P )-values)</th>
<th>Group comparisons (( P )-values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L inf front → L ant hipp</td>
<td>0.00 (0.18)</td>
<td>0.08 (0.21)</td>
<td>0.04 (0.25)</td>
<td>0.20</td>
<td>0.54</td>
</tr>
<tr>
<td>R inf front → R ant hipp</td>
<td>0.05 (0.28)</td>
<td>0.08 (0.22)</td>
<td>-0.02 (0.26)</td>
<td>0.84</td>
<td>0.32</td>
</tr>
<tr>
<td>L ant hipp → L inf front</td>
<td>-0.19 (1.23)</td>
<td>-0.22 (0.82)</td>
<td>0.63 (0.85)</td>
<td>0.69</td>
<td>0.11</td>
</tr>
<tr>
<td>R ant hipp → R inf front</td>
<td>-0.12 (1.23)</td>
<td>-0.01 (0.98)</td>
<td>-0.13 (1.04)</td>
<td>0.64</td>
<td>0.95</td>
</tr>
<tr>
<td>L inf front → L post hipp</td>
<td>0.07 (0.14)</td>
<td>0.12 (0.20)</td>
<td>0.11 (0.29)</td>
<td>&lt;0.01</td>
<td>0.77</td>
</tr>
<tr>
<td>R inf front → R post hipp</td>
<td>0.09 (0.24)</td>
<td>0.07 (0.22)</td>
<td>0.12 (0.76)</td>
<td>0.02</td>
<td>0.85</td>
</tr>
<tr>
<td>L post hipp → L inf front</td>
<td>0.72 (0.85)</td>
<td>0.20 (0.82)</td>
<td>0.77 (0.65)</td>
<td>&lt;0.01</td>
<td>0.12</td>
</tr>
<tr>
<td>R post hipp → R inf front</td>
<td>1.11 (0.33)</td>
<td>0.32 (0.89)</td>
<td>0.65 (0.71)</td>
<td>&lt;0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Group mean estimates and SD (in brackets) are reported for endogenous connections, with those that were significantly greater than zero across the three groups highlighted in bold. We also report the \( P \)-values of group differences, which were identified using a series of ANOVAs with significant effects highlighted in bold (statistical threshold \( P < 0.025 \)).

L = left; R = Right; inf = inferior; front = frontal; ant = anterior; post = posterior; hipp = hippocampus.

Discussion

The aim of the present investigation was to examine prefronto-hippocampal interactions in the ‘ARMS’ and in first episode schizophrenia using fMRI in conjunction with DCM (Friston et al., 2003; Mechelli et al., 2003).
between regions are independent of inferences about regional activation in the same regions (Stephan et al., 2007). Furthermore, this finding indicates that the posterior hippocampus was indeed engaged during task performance, despite the loss of strong regional activation. We found that the intrinsic connection from the right posterior hippocampus to the right inferior frontal gyrus was impaired in first episode patients and individuals with ARMS, relative to controls during a DMTS task (Fig. 1D). The intrinsic connection strength refers to the influence that one area exerts over another, regardless of task conditions. As a difference in intrinsic connection strength might reflect differences in IQ between groups, and the controls had higher NART scores than the other groups, we tested whether the strength of this intrinsic connection was related to IQ within each group. However, no significant correlation was found in the first episode ($r = 0.57, P = 0.14$), ARMS ($r = -0.31, P = 0.24$) or control groups ($r = 0.27, P = 0.93$). Second, the difference in intrinsic connection strength may reflect neuropsychological changes associated with antipsychotic medication (Honey and Bullmore, 2004). The groups also differed with respect to exposure to antipsychotic medication, with only the first episode group having had antipsychotic treatment. We explored the possibility that medication could have accounted for the difference in connection strength by examining the correlation between the strength of the intrinsic connection and exposure to antipsychotic medication within the first episode group. There was no significant correlation with either the cumulative dose ($r = -0.10, P = 0.83$) or the duration of treatment ($r = -0.357, P = 0.31$) within the first episode group. We also note that, so far, no studies have demonstrated a significant influence of IQ or antipsychotic medication on the functional coupling between the hippocampus and the inferior frontal gyrus.

Our result is consistent with previous reports of an impairment of functional integration in schizophrenia (Fletcher et al., 1999; Schlosser et al., 2003; Shergill et al., 2003; Honey et al., 2005; Meyer-Lindenberg et al., 2005; Mechelli et al., 2006) and in particular, adds to the evidence for a specific disturbance of the functional coupling between prefrontal and hippocampal regions (Weinberger et al., 1992; Heckers et al., 1999; Meyer-Lindenberg et al., 2005; Zhou et al., 2007, 2008). However, our data extend these previous findings with respect to three main aspects.

First, previous studies investigated the coupling between prefrontal cortex and hippocampal formation in terms of temporal correlations, that is ‘functional connectivity’ (Friston et al., 1993a), and could not therefore indicate the direction of the impaired connection. By using dynamic casual modelling (Friston et al., 1993b), we were able to show that the altered connectivity was from the right posterior hippocampal formation to the right inferior frontal gyrus. Although this result needs to be replicated, it appears to be inconsistent with cognitive models of schizophrenia in which a top–down context-processing disturbance is thought to be responsible for cognitive deficits and to bias the selection of behavioural responses (Frith and Done, 1988; Cohen and Servan-Schreiber, 1992; Braver et al., 1999). Our finding seems to support the notion that a disruption of bottom–up neural mechanisms might sustain at least some of the neurocognitive features of schizophrenia (Broome et al., 2005), and is consistent with data from a previous study in which a disruption of bottom–up effective connectivity was evident in chronic schizophrenic patients with auditory verbal hallucinations (Mechelli et al., 2007).

Second, we investigated the interaction between hippocampal and prefrontal cortex function in patients who had just developed schizophrenia, as opposed to chronic patients, and in ARMS subjects who were not psychotic but have a high risk of becoming psychotic. This minimized the risk that the findings were secondary to an effect of chronic illness or its treatment. Both functional and structural abnormalities in schizophrenia may change over the course of psychiatric disorders (for a review see Fusar-Poli et al., 2007) and antipsychotic medication can modify activation during cognitive tasks (Mendrek et al., 2005; Tan et al., 2005). We found a significant decrease in the strength of the intrinsic connection from the right posterior hippocampal formation and right inferior frontal gyrus in both first episode patients and subjects at high risk. An anecdotal examination of the group specific endogenous connections suggested that subjects at high risk expressed an even greater decrease of functional connectivity than first episode patients; nevertheless a direct comparison indicated that the difference between the two groups was not significant (two-sample $t$-test; $P = 0.33$). This observation of decreased intrinsic connectivity in both first episode patients and subjects at high risk is consistent with a recent report of abnormal functional connectivity between prefrontal regions and more posterior cortical and subcortical regions in the relatives of patients with schizophrenia (Whalley et al., 2005), and with evidence that the ARMS is associated with focal neuroimaging abnormalities in prefrontal and medial temporal cortex (Pantelis et al., 2003; Morey et al., 2005; Borgwardt et al., 2007; Broome et al., 2009). Our findings suggest that a disruption of hippocampal–prefrontal connectivity is evident at the onset of schizophrenia and also in subjects who are not psychotic but are at high risk of developing the disorder. This suggests that the disruption of connectivity represents a correlate of increased vulnerability to psychosis.

Third, we found that the alteration in intrinsic connectivity with the inferior frontal gyrus was specific to the posterior part of the right hippocampus. Although the functional parcellation of hippocampal sub-regions is still unclear, a number of previous neuroimaging studies of memory in healthy subjects (Maguire et al., 1996; Lepage et al., 1998; Strange et al., 1999) have reported that the retrieval of previously seen objects, pictures and complex visual scenes is often associated with activation in the caudal portion of the hippocampal formation, suggesting an involvement of posterior hippocampus in the retrieval of familiar stimuli. This is consistent with evidence that posterior hippocampal volume was significantly increased in taxi drivers, and was correlated with the time they had spent in the job (Maguire et al., 2000). In contrast, the encoding of previously unseen object and pictures has been associated with activation in the anterior hippocampal region (Tulving, 1996; Lepage et al., 1998; Rombouts et al., 1999, 2000; Strange et al., 1999; Weiss et al., 2004). In the present study, we analysed activation associated with the correct recognition of previously presented stimuli, consistent with
greater involvement of posterior than anterior hippocampus. With respect to the laterality of the hippocampus (as opposed to its anterior/posterior division), right-sided activation has been repeatedly associated with the encoding and retrieval of objects, pictures, and abstract visual patterns (Martine et al., 1997; Kelley et al., 1998; Golby et al., 2001), whereas left-sided hippocampal activation has been associated with encoding and retrieval of meaningful and verbal stimuli (Martin et al., 1997; Kelly et al., 1998; Weiss et al., 2004; Rametti et al., 2007). Our findings of impaired connectivity between the right hippocampal region and the prefrontal cortex may thus reflect the nature of the experimental task, which involved the visual processing of complex abstract patterns. In addition, the disruption of right-sided prefronto-hippocampal connectivity in both first episode patients and individuals with an ARMS is consistent with previous finding of impaired performance in visual but not verbal memory tests in individual at high risk of psychosis prior to the onset of psychosis (Brewer et al., 2005).

Whether the anterior and posterior parts of the hippocampus are differentially affected in schizophrenia is unclear, with some studies suggesting that the anterior part is more susceptible and other studies implicating posterior regions (Bilder et al., 1995; Narr et al., 2001; Narr et al., 2002; Szeszko et al., 2002, 2003; Pegues et al., 2003). However, to our knowledge, the regional specificity of abnormal connectivity between the hippocampal formation and the prefrontal cortex has not yet been investigated. We might suggest that a disturbance of neural interactions between posterior hippocampus and prefrontal cortex may be detected early in the neuropathological course of schizophrenia and be more evident in the right than in the left hemisphere during an object working memory task. A limitation of the present study is that our characterization of prefronto-hippocampal coupling was based on all components of the object working memory task combined; future investigations could examine how prefronto-hippocampal coupling is differentially modulated during encoding, maintenance and recognition.

Interestingly, our analysis of regional responses showed that the anterior and posterior hippocampus did not show different regional activation across our experimental groups and maintenance delays. This finding seems to be consistent with a previous behavioural study, which has not shown long delay-dependent effects for object working memory in first episode schizophrenia-form psychosis and established schizophrenia (Mathes et al., 2005). Nevertheless, our analysis of effective connectivity revealed that the functional coupling between right posterior hippocampus and the prefrontal cortex was altered in patients and ARMS subjects, relative to controls. These results are consistent with the idea that the neural correlates of schizophrenia are best characterized in terms of abnormal interactions within a distributed network of regions rather than localized deficits (Friston and Frith, 1995; Gold and Weinberger, 1995; Stephan et al., 2006).

In summary, using fMRI and dynamic casual modelling, in association with a DMTS task, we found that the intrinsic connection from the right posterior hippocampus to the right inferior frontal gyrus was impaired in both first episode patients and individuals with an ARMS, relative to controls. This suggests that a disruption of bottom-up hippocampal-prefrontal integration is evident not only at the onset of schizophrenia but also in subjects at high-risk of psychosis, and may therefore represent a correlate of increased vulnerability to psychosis rather than the disorder itself.

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References

Impaired prefronto-hippocampal connectivity

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