Altered awareness of action in schizophrenia: a specific deficit in predicting action consequences

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Patients suffering from schizophrenia may report unusual experiences of their own actions. They may either feel that external forces are controlling their actions or even their thoughts, or they may feel in control of events that in fact are not caused by their actions. Most theories link these disturbances in the sense of agency to deficits in motor prediction, resulting in a mismatch between predicted and actual sensory feedback at a central comparator mechanism. Such theories therefore can account for situations in which the sense of agency is reduced. However, other experiments as well as clinical observations show an enhanced rather than reduced sense of agency in schizophrenic patients. Here, we distinguish between a predictive and a retrospective mechanism where both contribute to the experience of agency, and show that schizophrenia is associated with a specific impairment to the predictive component. We measured subjective time estimates of self-initiated voluntary action (a key press) that were followed by a sensory effect (a tone). When the voluntary actions had a high probability of causing tones, healthy volunteers showed a predictive shift of the perceptual estimate of the action towards the tone, even on occasional trials where the tone was omitted. No such shift occurred in the absence of the tone on blocks when tones were less frequent. The predictive component of action awareness was calculated as the difference between time estimates on ‘action only’ trials from blocks with lower and higher tone probabilities. Schizophrenic patients lacked this predictive component of action awareness, showing a shift on ‘action only’ trials, regardless of the probability of the tone. Importantly, the schizophrenic deficit in predicting the relation between action and effect was strongly correlated with severity of positive psychotic symptoms, specifically delusions and hallucinations. Furthermore, the patients showed an exaggerated retrospective binding between action and tone, shifting the perceived time of action whenever the tone occurred, relative to when it did not occur. Our quantitative, implicit measures show how basic sensory and motor experience may be altered in acute psychosis. The enhanced sense of agency in schizophrenia reflects reliance on retrospection, rather than prediction, to associate actions with external events. The failure to predict the effects of one’s own actions may underlie the blurring and confusion in the relationship between the self and the world that characterizes acute psychosis.

Keywords: schizophrenia; action–perception matching system; sensorimotor; action monitoring
Introduction

Planning and executing actions in order to produce effects in the external environment is a central component of human life. These processes of intentional action involve both specific brain circuits (Haggard, 2008), but also produce a characteristic subjective experience, which has been called ‘sense of agency’ (Gallagher, 2000).

Schizophrenia is a widespread mental illness in which several aspects of cognition are impaired and disordered. An altered experience of one’s own action may underlie several of the first-rank symptoms of schizophrenia. For example, passivity phenomena and thought insertion may be conceptualized as a tendency to attribute one’s own actions and thoughts to external forces, respectively. Recent computational theories implying models of sensorimotor prediction (Wolpert and Ghahramani, 2000; Bays and Wolpert, 2007) suggest that signals generated by voluntary movement (re-afferences; Von Holst, 1996) are processed differently from signals of external origin (Shergill et al., 2003) and sensory input is cancelled or attenuated based on motor command signals (Voss et al., 2006, 2008). Specifically, an internal model predicts the sensory consequences of current motor commands, and compares this prediction with actual sensory input. Crucially, conscious perception reflects only the error generated by this comparison; that is, the difference between sensory signals and predicted re-afference, since there is no need to perceive what can already be predicted (Blakemore et al., 1998). It has been suggested that prediction based on efference copy may be compromised in schizophrenia (Frith, 1992; Lindner et al., 2005). On this view, positive symptoms such as delusions of control may occur because the comparator lacks a predictive input. Even internally generated information, such as one’s own thoughts and intentions, would then be perceived as originating externally (Blakemore et al., 2002).

This model therefore predicts reduced sense of agency in schizophrenia. However, this is at odds with a number of findings. For example, several studies asked patients to identify explicitly whether a visual signal corresponded to an action they had just made or not (Dapra et al., 1997; Franck et al., 2001; Fourneret et al., 2002). All show that patients are more likely than controls to identify an action as their own. That is, patients tend to perceive actions as their own, or originating internally, rather than externally as comparator theories would predict. The combination of reduced prediction but excessive agency in schizophrenia cannot readily be explained by comparator models.

One objection to this line of reasoning appeals to the distinction between explicit judgements of agency used in such self-recognition studies, and the feeling or sense of agency that accompanies most voluntary actions (Synofzik et al., 2008). This experience of agency forms a background to all our interactions with the world, and can therefore be elusive in laboratory experiments. However, the key mechanism underlying sense of agency is the association between one’s own action and an external effect. This association produces the experience of fluently controlling one’s own actions, and through them, the external world. Interestingly, such associations produce systematic distortions of time perception linked to voluntary action. People perceive their own actions (e.g. a key press) as occurring later when they are followed by an external effect (e.g. a tone), compared to actions not followed by such effects. Thus, linkage with an external effect alters action awareness (Fig. 1). This ‘intentional binding’ provides a useful implicit measure of the sense of agency.

The linkage between action and effect could be generated in two ways, either predictively or retrospectively. A predictive sense of agency means that an action is predicted to produce a given effect, whereas retrospective sense of agency means that one infers retrospectively that one’s action caused the effect. Moore and Haggard (2008) showed that intentional binding involved both predictive and retrospective components. First, when participants frequently experienced key presses followed by tones, they perceived the time of action as shifted towards the anticipated tone, even on rare trials where no such tone occurred, suggesting that they predicted the tone when they pressed the key. Indeed, the shift was absent on blocks where tones were less frequent and therefore less predictable. Second, a shift in action awareness also occurred when a tone was not highly predictable, but did actually occur. In the absence of prediction, the actual occurrence of the tone retrospectively changed the experience of action.

Here, we use this paradigm to investigate the abnormal experience of instrumental action in schizophrenia. Previous studies

![Figure 1](http://brain.oxfordjournals.org/bjs327/fig1.jpg)

**Figure 1** ‘Intentional binding’ between perceived time of action and effect. (A) Subjects make a voluntary action (key press) to evoke an effect (a tone) occurring 250 ms later. (B) The perceived time of actions occurring alone are estimated in a baseline condition. Note that the perceived onset of the event may not coincide with its physical onset. (C) When action and tone occur together, the perceived time of the action shifts later in time from the baseline value (dotted line), towards the tone. (D) If the probability of the action causing the tone is high, awareness of action is shifted towards the predicted time of the tone, even on occasional trials where the tone is omitted. For discussion of action-related changes in the perceived time of effects, see Haggard et al. (2002).
focused on attenuation of perceived somatic consequences of action (Blakemore et al., 2000; Shergill et al., 2005) in schizophrenia. However, low-level anticipatory motor control was reported to be normal (Bulot et al., 2007). We investigate how the external effects of a voluntary action influence the experience of the action itself. We show, for the first time, that the subjective experience of action in schizophrenia is not based on the same predictive mechanisms as in healthy volunteers. However, schizophrenics are still able to associate actions and effects, and in fact do so rather more than a control group. Specifically, the patients’ experience of action-effect linkage is based not on predictions, but on a separate mechanism of retrospective inference triggered by the external effect of action. Our study provides the first convincing explanation of why schizophrenia may involve both impaired action prediction, together with a tendency to overestimate one’s own agency.

Materials and methods

Participants

Twenty-four right-handed patients with paranoid schizophrenia according to Diagnostic and Statistical Manual of Mental Disorders-IV and International Statistical Classification of Diseases and Related Health Problems-10 criteria and 24 age- and gender-matched healthy control subjects were included in the study. Participants suffering from dementia, neurological illnesses, severe brain injuries or brain tumours at the time of the examination were excluded from the sample. Participants had no other psychiatric axis I disorder (Structured Clinical Interview for Diagnostic and Statistical Manual of Mental Disorders-IV (First et al., 2001)) and no current drug abuse or past history of drug dependence (Structured Clinical Interview and random urine drug testing).

After a complete description of the study, written informed consent was obtained from each subject. The protocol was approved by the Local Ethical Committee of the Charité University Hospital in Berlin, and followed the Declaration of Helsinki.

All patients were of the paranoid subtype (two female, age range 20–66 years). They were recruited from the Department of Psychiatry, Charité University Hospital, Berlin (22 in-patients, 2 out-patients) and were on standard clinical doses of atypical (17 patients), typical (3 patients) or a combination of typical and atypical (4 patients) neuroleptic medication. The mean duration of illness was 9.3 ± 9.8 years. Supplementary Table 2 shows details of demographic, pathology and drug information for the schizophrenic and healthy control samples.

A standardized biographic interview and a test of hand preference (Edinburgh Inventory; Oldfield, 1971) were performed with each participant after written informed consent was obtained. Extrapyramidal motor side-effects were assessed using the Extrapyramidal Symptom Scale (Simpson and Angus, 1970). Attention was assessed with the d2 test (Brickenkamp, 2002; n = 16). Psychopathology was assessed using Positive and Negative Syndrome Scale (Kay et al., 1987; n = 20, due to unexpected discontinuation of in-patient treatment in four patients).

Procedure

The experimental procedure was completed by both healthy controls and schizophrenic patients; the trial structure used in the study is presented in Fig. 2. Participants started each trial themselves by pressing a button with the left hand. On each trial, participants performed voluntary, self-paced key presses with their right index finger. The participant’s task was to judge the time of this key press, relative to a clock shown on a computer screen. The clock hand rotated every 2560 ms, began at a random location prior to the key press and ended at a random time after the key press. These timing judgements were made in two separate experimental conditions. In a 50% effect probability condition, the key press caused a tone to occur at random on 50% of the trials. In a 75% effect probability condition, the key press caused a tone to occur at random on 75% of the trials. If present, the tone always occurred 250 ms after the key press. Once the clock stopped, participants verbally reported the position of the clock hand when they pressed the button.

Participants completed two blocks of action timing judgements, for each effect probability (50 and 75%). Each block consisted of 32 trials. In addition, there was a single baseline condition of 32 trials, in which participants made a key press at a time of their choosing, but no tones occurred. Mean baseline action estimates are subtracted from mean action estimates in the experimental conditions. The order of block completion (both effect probability and baseline) was randomized anew for each participant. The experimental procedure was completed in a single 45-min session.

Statistical analyses

In order to isolate the respective predictive and retrospective contributions to action experience in controls and schizophrenic patients, we contrasted specific cells of our factorial design (Fig. 3). First, to isolate the predictive contribution, we subtracted the shifts in the temporal experience of action on ‘action only’ trials in 50% effect probability condition, from shifts on action ‘only trials’ in the 75% condition. By focusing solely on ‘action only’ trials, we removed the retrospective influence of the tone (sensory effect) on action awareness. The resulting change in action judgements reflects the impact of increasing effect probability, and thus the putative engagement of an implicit predictive mechanism.

Second, to isolate explicit retrospective contributions, we subtracted shifts in the temporal experience of action on ‘action only’ trials in the 50% effect probability condition from shifts on ‘action and tone’ trials in the 50% effect probability condition. We reduced the influence of predictability on this estimate, by focusing on the 50% condition where predictability was low. By then comparing ‘action only’ and ‘action and tone’ trials, we could assess the influence of the tone on the awareness of action, and thus the role of retrospection in action awareness. Taken together, these contrasts provided us with estimates of both predictive and retrospective processes in the experience of action.

Results

On each trial, participants performed voluntary, self-paced key presses with their right index finger. The participants’ task was to judge the time of this key press, using a clock with a hand rotating about its centre (see ‘Materials and methods’ section for more details). Judgement error for each key press was calculated as the difference between the actual key press time and the judged time. The patients generally performed the time judgement task well: the standard deviation (SD) of repeated timing judgements across trials was similar to controls. [schizophrenic
mean ± SD = 97 ± 42 ms, control mean ± SD = 80 ± 38 ms: independent samples t-test, $P = 0.156$ (two-tailed).

In our ‘baseline action only’ condition, key presses were never followed by tones. Baseline judgements varied both within- and between-groups. However, there was no significant difference for ‘baseline action only’ judgements between patients and healthy controls [mean schizophrenic baseline action: $-19.3$ (SD = 83.6), mean control baseline action: $-56.6$ (SD = 47.3), $t(46) = 1.851$, $P = 0.071$ (two-tailed)]. Interestingly, the patients’ performance in the baseline condition showed smaller judgement errors than controls, i.e. more accurate judgements. This rules out the possibility that patients had a general difficulty with the timing task. We have shown that baseline judgements reflect factors of the cross-modal timing task common to all conditions, such as the division of attention between action and clock (Haggard and Cole, 2007). In contrast, changes in judgement across the experimental conditions provide specific information about action representation in different conditions. Here, timing judgements were made in two separate experimental conditions. In a 50% effect probability condition, the key press caused a tone to occur at random on 50% of the trials. In a 75% effect probability condition, the key press caused a tone to occur at random on 75% of the trials. If present, the tone sounded after a delay of 250 ms from key press onset.

Average time estimates in the ‘baseline action only’ condition were subtracted from average time estimates in each of the tone probability conditions to give a judgement shift, or change in perceived time of action. The judgement shift measures the binding, or linkage, between the action and the tone. A positive shift indicates a delay in the awareness of action towards the tone, corresponding to the intentional binding effect and used as an implicit measure of sense of agency (Haggard et al., 2002; Moore and Haggard, 2008).
Intentional binding in schizophrenic patients and controls

Table 1 shows this binding measure, i.e. shift in the perceived time of action towards tone, relative to baseline, in each condition for schizophrenic patients and controls. There was a generally positive binding effect: the perceived time of actions in experimental blocks was later than the perceived time of actions in baseline blocks (one-sample $t$-test, $P = 0.008$). Binding effects were significantly greater in patients than in controls, as predicted from previous studies of both binding (Haggard et al., 2003) and other agency measures (Franck et al., 2001; schizophrenic mean = 30 ms, control mean = 6 ms; independent samples $t$-test, $P = 0.03$ one-tailed).

The role of prediction and retrospection in schizophrenic patients and controls

Inspection of Table 1 also suggests that the intentional binding effect in patients with schizophrenia and controls is modulated by different factors. In the patients, most binding was found when the tone was present, rather than absent. This suggests a greater influence of sensory driven, retrospective processes on action awareness in patients. In the controls, most binding was found in the higher effect probability condition. This suggests a greater influence of predictive processes action on awareness in controls.

We formally investigated the influence of predictive and retrospective processes on action awareness (see ‘Materials and methods’ section for more details). To isolate the predictive contribution, we subtracted the average intentional binding effect for actions on ‘action only’ trials in 50% effect probability condition from the average intentional binding effect for actions on ‘action and tone’ trials in the same 50% effect probability condition (Fig. 3). This contrast was confined to conditions with a low probability of the tone occurring to minimize the contribution of predictive processes.

The predictive and retrospective components of action binding were compared between patients and controls. Inspection of Fig. 4 reveals that control subjects show a strong predictive component of intentional binding, and only minimal retrospective contribution. In contrast, schizophrenic patients show a strong retrospective component of binding, but no predictive component.

We performed a mixed design $2 \times 2$ ANOVA on the process dependent shifts, with a between subjects factor of Pathology (schizophrenic versus control), and a within subjects factor of Process (predictive versus retrospective). There was no main effect of Process [$F(1,46) = 0.021, P = 0.90$] or Pathology [$F(1,46) = 0.015, P = 0.90$]. However, there was a significant interaction between Pathology and Process [$F(1, 46) = 4.45, P = 0.040$), as shown by the cross-over effect in Fig. 4.

Table 1 Mean judgement error for action estimates (ms) in both the control and schizophrenic participants (SE across subjects)

<table>
<thead>
<tr>
<th>Group</th>
<th>Condition</th>
<th>Trial type</th>
<th>Mean (SE) judgement error for key press (ms)</th>
<th>Mean (SE) shift from baseline (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls</td>
<td>Baseline</td>
<td>‘Action only’</td>
<td>$-56$ (10)</td>
<td>$-0.3$ (9)</td>
</tr>
<tr>
<td></td>
<td>50% effect probability</td>
<td>‘Action only’</td>
<td>$-56.3$ (13)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75% effect probability</td>
<td>‘Action and tone’</td>
<td>$-55.3$ (14)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>‘Action only’</td>
<td>$-44$ (13)</td>
<td>$12$ (10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>‘Action and tone’</td>
<td>$-47$ (13)</td>
<td>$9$ (10)</td>
</tr>
<tr>
<td>Schizophrenics</td>
<td>Baseline</td>
<td>‘Action only’</td>
<td>$-19$ (17)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50% effect probability</td>
<td>‘Action only’</td>
<td>$5$ (20)</td>
<td>$23.8$ (9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>‘Action and tone’</td>
<td>$17$ (20)</td>
<td>$36$ (10)</td>
</tr>
<tr>
<td></td>
<td>75% effect probability</td>
<td>‘Action only’</td>
<td>$5$ (20)</td>
<td>$23.6$ (10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>‘Action and tone’</td>
<td>$16$ (20)</td>
<td>$35$ (10)</td>
</tr>
</tbody>
</table>
The relationship between specific symptoms and predictive/retrospective contributions to action awareness

We expected a negative correlation between positive symptoms and prediction-dependent shifts in action awareness (stronger positive symptoms should be associated with less prediction). This assumption was based on previous reports about abnormalities in action awareness and associations with positive symptoms, particularly delusions and hallucinations (Daprati et al., 1997; Blakemore et al., 2000). Therefore, one-tailed significance levels were used.

As expected, patients with higher overall scores for positive symptoms (Positive and Negative Syndrome Scale positive symptoms total score) showed smaller prediction-dependent shifts in action awareness (r = −0.424, P = 0.031, Supplementary Fig. 1). More specifically, within the cluster of positive symptoms there was a negative correlation with delusions (r = −0.379, P = 0.05, Supplementary Fig. 2) and with hallucinatory behaviour (r = −0.560, P = 0.005, Supplementary Fig. 3). In order to exclude medication effects, we performed an additional partial correlation analysis, which included the drug dose (based on chlorpromazine equivalent calculations (Woods, 2003)) as a covariate. Significance levels then slightly changed (for Positive and Negative Syndrome Scale total positive score: r = −0.433, P = 0.032; for delusions subscore: r = −0.378, P = 0.055 and for hallucinatory behaviour: r = −0.567, P = 0.006).

Finally, we investigated the relation between shifts in action awareness and several other potential factors. No significant correlations with either predictive or retrospective shifts were found for drug dose (again, based on chlorpromazine equivalent calculations) (Woods, 2003), age, duration of illness [all r < 0.28 and ≥−0.24 with P > 0.175 (two-tailed) for n = 24] or attentional performance [measured with the d2 test (Brickenkamp, 2002); r = −0.440, P = 0.088 for retrospective and r = −0.06, P = 0.825 for predictive shifts; n = 16]. A significant negative correlation between smoking and retrospective binding (r = −0.49, P = 0.015) was found but no significant relation between smoking and predictive binding (r = −0.17, P = 0.42).

This overall pattern of results suggests that the changes in predictive experience of action in our experimental measures reflect the disease process itself, rather than any obvious confounding factors.

Discussion

We measured the perceived time of voluntary actions in schizophrenic patients and normal controls. The temporal shift in perception of action towards a subsequent tone provides an implicit measure of the linkage between experience of one’s own internally generated actions and their consequences in the external world. We found that actions were perceived significantly later when tones could occur than in a baseline block without tones. This ‘intentional binding’ effect (Haggard et al., 2002) has been interpreted as evidence that the internal representation of action is attracted by the representation of the external consequence of action. This is consistent with ideomotor theories of action (James, 1998; Hommel et al., 2001). Patients showed a trend towards a more pronounced binding effect than controls, confirming previous reports of enhanced agency in schizophrenia (Haggard et al., 2003).

Awareness of action plays an important role in recent computational models of schizophrenia. These models hypothesize an impairment of efference-based prediction in schizophrenia (Frith, 1992) leading to a reduced sense of agency over one’s own immediate bodily movements. Indeed, schizophrenic patients experience the immediate bodily consequences of their own actions, such as tickling, as being externally triggered (Blakemore et al., 2000; Shergill et al., 2005). On the other hand, studies of self-recognition in schizophrenia produced the opposite pattern of results. Schizophrenic patients were more willing than controls to link distorted artificial feedback to their own actions. This suggests an excess rather than a reduced sense of agency, as found in previous studies (Franck et al., 2001; Fourneret et al., 2002).

In our study, the consequence of action (a tone) is obviously an external event, and has no isomorphism with the action itself. Moreover, our participants reported the time of their action, and the external event was in fact irrelevant to the task. Nevertheless, we showed an increased influence of the arbitrary external tone on experience of action in schizophrenics, analogous to the increased self-attribution reported previously (Franck et al., 2001; Fourneret et al., 2002). We conclude that excessive linkage between internally generated action and external sensory events is a fundamental feature of action experience in schizophrenia.

Our experimental design allowed us to distinguish two quite different mechanisms that both contribute to the experienced linkage between actions and their external consequences. Humans and animals predict the effects of voluntary action on the basis of previous acquired experience. Indeed, instrumental learning is essential for goal-oriented behaviour (Dickinson, 1980). We varied the extent to which the participants’ experience in each block of the experiment would support such predictions, by setting the frequency of tones to either 50 or 75% of trials. We operationally defined the predictive contribution to action experience as the difference between perceived time of actions that were not in fact followed by tones on higher, relative to lower tone frequency blocks. In principle, any two levels of tone probability could be used to define an ordinal difference in predictability in this way. Our choice of 50 and 75% was based on previous studies with healthy volunteers (Moore and Haggard, 2008). An operational definition based on more widely separated probabilities might be more sensitive to the contribution of prediction. However, it might also be less efficient and less robust, since a very high tone probability would leave only a few of the ‘action only’ trials that isolate the predictive component.

On the other hand, an event that happens to occur after action may alter or retrospectively alter the experience of action itself. Indeed, retrospective influence of a later event on the mental representation of an earlier event seems to be a general principle of conscious experience (Geldard and Sherrick, 1972; Dennett, 1991). Such retrospective post-diction may even be sufficient to
generate a sense of agency (Wegner and Wheatley, 1999; Wegner, 2003). In our design, this retrospective component of agency was operationalized by comparing the perceived time of actions that were followed by tones with the perceived time of actions not followed by tones, in the 50% tone frequency condition where prediction was less likely. We found a striking dissociation between schizophrenics and controls in the importance of the predictive and retrospective influences on action experience. In the schizophrenic group, binding of actions towards tones did not vary with the actual predictability of the tone, but was equal in 50 and 75% tone frequency conditions. In addition, action binding in patients was strongly modified by the actual occurrence of the tone in both conditions, suggesting a strong retrospective influence. As such, their experience of agency appeared to be driven by immediate sensory evidence that a tone followed a particular action, without any reference to an internal model specifying the prior probability of a tone given an action. Conversely, in the control group, intentional binding of actions towards tones arose almost entirely from predictive mechanisms. The controls’ data showed that they expected tones to occur in the high-tone probability blocks, and indeed experienced their actions with reference to the expected future tone.

Previous studies also demonstrated greater levels of overall binding in schizophrenia (Haggard et al., 2003). However, the present study goes further by revealing the mechanisms responsible for the patients’ deficits. We identify, for the first time, a specific deficit in one particular mechanism that contributes to the experience of agency, namely predictive anticipation of external effects of one’s own action. Whereas healthy volunteers appeared to predict the tone’s occurrence on the basis of their action when the conditional probability of tones was high, we found no evidence for such prediction in schizophrenics. Rather, the patients appeared to experience the linkage between action and tone as a surprising contingency discovered anew each time it occurred.

We now consider some possible alternative explanations of our results. First, schizophrenics performed the task well, ruling out explanations based on general cognitive impairments, poor time perception or working memory deficits. In particular, their time judgements were as consistent across repeated trials as those of controls, and their mean time judgements in baseline conditions were actually more accurate than those of controls. This suggests that the key cognitive functions underlying our time estimation method, such as cross-modal synchronization or attention to the clock, did not differ between patients and controls. Second, our results cannot be explained in terms of a schizophrenic deficit for difficult but not easy tasks. For example, schizophrenics might be expected to have difficulty in processing the more complex situation of binding trials, where action and tone occur together, compared to trials where a single event occurs alone. However, our key finding, namely no predictive shift of action awareness in schizophrenics, is based on action-only trials. Third, several studies have noted schizophrenic deficits in perception and production of temporal durations (Caroll et al., 2009; Waters and Jablensky, 2009). However, these deficits could not account for the sensitivity of ‘action only’ trials to the probability of an ensuing tone. Finally, we show in the results section that general factors such as age, duration of illness, medication, attention or nicotine dependence did not convincingly account for the patients’ specific deficits.

We found associations between key schizophrenic symptoms and deficits in prediction across schizophrenic individuals. Specifically, we found that a higher incidence of ‘first rank’ positive symptoms, such as delusions and hallucinations, was associated with a reduced predictive component of intentional binding. These associations were not simply due to confounding factors such as medication or general cognitive impairment. This confirms the specific link between prediction deficits and the symptom of psychosis, as opposed to the mere diagnosis of ‘schizophrenia’.

Another recent study of explicit judgement of agency in schizophrenics also showed an abnormal weighting between sensory input and internal predictions about one’s own actions and their consequences (Synofzik et al., 2010). The authors propose that agency arises from integrating both predictions and sensory evidence (cf. Moore and Haggard, 2008). On this view, external cues and internal predictions are combined to generate experiences (Moore et al., 2010) or judgements (Synofzik et al., 2010) of agency. The precise interaction between the independent predictive and retrospective components in healthy volunteers remains unclear. One possibility is a dynamic sequence, with advance prediction of effects during action preparation, and retrospective adjustment once sensory feedback is available. Another possible interaction is reciprocation, with one mechanism strategically compensating for any failures in the other. Irrespective of the precise form of interaction between the two mechanisms, schizophrenia might involve abnormalities in their integration. For example, Fletcher and Frith (2009) as well as Corlett et al. (2009) have recently suggested that positive symptoms in schizophrenia can be explained as a disturbance in a hierarchical Bayesian framework.

The neurobiological basis of schizophrenia has received considerable attention. On the one hand, explanations based on imbalances in dopamine (Carlsson, 1988; Meyer-Lindenberg et al., 2002) and glutamate (Carlsson et al., 1999) concentrations aim to provide a general functional concept, e.g. ‘aberrant salience’ (Heinz, 2002; Kapur, 2003) or excessive association (Escobar et al., 2002). These views might explain the present results by suggesting that external events become peculiarly salient in schizophrenia, and thus ‘override’ internal events. On the other hand, neuroanatomical hypotheses, often based on neuroimaging data, have made several specific but independent links between particular brain structures and schizophrenic deficits on tasks such as agency judgements (Farrer et al., 2004), violation of expectations (Corlett et al., 2007) and fear processing (Williams et al., 2004). Several research lines confirm that frontal motor areas and parietal monitoring areas jointly generate the sense of control over one’s own actions (Desmurget et al., 2009). To this extent, our results could reflect schizophrenic abnormalities in frontal and parietal processing, such as those reported previously (Spence et al., 1997).

Successful goal-directed action and, indeed, mental life in general, implies understanding the interactions between the self and the world (Kircher and David, 2003). Predicting the specific consequence of one’s actions is a fundamental example of this...
capacity. Our results suggest that psychotic patients lack this predictive structuring link between the self and external events. Our data provide a quantitative, implicit measure of how basic sensory and motor experience may be altered in psychosis. These changes point to a specific failure to predict the external effects of one’s own action, and a concomitant blurring and confusion of the relation between the self and the world.

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**Supplementary material**

Supplementary material is available at Brain online.

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