

# Misattributions of agency in schizophrenia are based on imprecise predictions about the sensory consequences of one's actions

Matthis Synofzik,<sup>1,2</sup> Peter Thier,<sup>1</sup> Dirk T. Leube,<sup>3</sup> Peter Schlotterbeck<sup>4</sup> and Axel Lindner<sup>1</sup>

1 Department of Cognitive Neurology, Hertie-Institute for Clinical Brain Research, University of Tübingen, 72076 Tübingen, Germany

2 Department of Neurodegeneration, Hertie-Institute for Clinical Brain Research, University of Tübingen, 72076 Tübingen, Germany

3 Department of Psychiatry, University Hospital Marburg, Rudolf-Bultmann-Straße 8, 35039 Marburg, Germany

4 Department of Psychiatry, University Hospital Tübingen, Osianderstraße 24, 72076 Tübingen, Germany

Correspondence to: Matthis Synofzik,  
Department of Neurodegeneration,  
Hertie-Institute for Clinical Brain Research,  
Hoppe-Seyler-Straße 3,  
72076 Tübingen,  
Germany  
E-mail: matthis.synofzik@uni-tuebingen.de

Correspondence may also be addressed to: Axel Lindner,  
Department of Cognitive Neurology,  
Hertie-Institute for Clinical Brain Research,  
Hoppe-Seyler-Straße 3,  
72076 Tübingen,  
Germany  
E-mail: a.lindner@medizin.uni-tuebingen.de

The experience of being the initiator of one's own actions seems to be infallible at first glance. Misattributions of agency of one's actions in certain neurological or psychiatric patients reveal, however, that the central mechanisms underlying this experience can go astray. In particular, delusions of influence in schizophrenia might result from deficits in an inferential mechanism that allows distinguishing whether or not a sensory event has been self-produced. This distinction is made by comparing the actual sensory information with the consequences of one's action as predicted on the basis of internal action-related signals such as efference copies. If this internal prediction matches the actual sensory event, an action is registered as self-caused; in case of a mismatch, the difference is interpreted as externally produced. We tested the hypothesis that delusions of influence are based on deficits in this comparator mechanism. In particular, we tested whether patients' impairments in action attribution tasks are caused by imprecise predictions about the sensory consequences of self-action. Schizophrenia patients and matched controls performed pointing movements in a virtual-reality setup in which the visual consequences of movements could be rotated with respect to the actual movement. Experiment 1 revealed higher thresholds for detecting experimental feedback rotations in the patient group. The size of these thresholds correlated positively with patients' delusions of influence. Experiment 2 required subjects to estimate their direction of pointing visually in the presence of constantly rotated visual feedback. When compared to controls, patients' estimates were significantly better adapted to the feedback rotation and exhibited an increased variability. In interleaved trials without visual feedback, i.e. when pointing estimates relied solely on internal action-related signals, this variability was likewise increased and correlated with both delusions of influence and the size of patients' detection thresholds as assessed in the first experiment. These findings support the notion that delusions of

influence are based on imprecise internal predictions about the sensory consequences of one's actions. Moreover, we suggest that such imprecise predictions prompt patients to rely more strongly on (and thus adapt to) external agency cues, in this case vision. Such context-dependent weighted integration of imprecise internal predictions and alternative agency cues might thus reflect the common basis for the various misattributions of agency in schizophrenia patients.

**Keywords:** agency; schizophrenia; efference copy; self; perception; optimal cue integration; Bayes

**Abbreviations:** PD=pointing direction; SAPS=Scale for the Assessment of Positive Symptoms

## Introduction

The neurobiology of bodily self-representation has been largely inspired by the 'comparator model' (Frith, 1992; Frith *et al.*, 2000). According to this account, the sensory consequences of one's behaviour can be predicted based on internal action-related information such as an efference copy of a motor command (von Holst and Mittelstaedt, 1950), corollary discharge (Sperry, 1950) and/or proprioception (Bell, 2001). By comparing this 'internal prediction' with the sensory afference, self-produced sensory information can be distinguished from externally caused events. In case of a match, the afference is interpreted as a result of our own actions. In case of a mismatch, the difference is registered as externally caused. In fact, both psychophysical and electrophysiological studies show that the constant comparison between internal predictions and external information ensures that we correctly attribute self-produced sensations to our own agency rather than to external causal forces (Blakemore *et al.*, 1999; Bell, 2001; Bays *et al.*, 2005; Lindner *et al.*, 2005; Synofzik *et al.*, 2006; Crapse and Sommer, 2008b; Dicke *et al.*, 2008). This mechanism allows us, for instance, specifically to cancel out the visual flow due to our own pursuit eye movements, thereby guaranteeing the perception of a stable world despite self-motion (Haarmeier *et al.*, 2001; Lindner *et al.*, 2005).

The previous example highlights only one of the many situations in which a reliable distinction between self-produced and externally produced sensory events is needed. It might be this general ability to attribute self-agency to sensory events that is severely impaired in schizophrenia patients suffering from delusions of influence: patients experiencing this first rank symptom and hallmark of schizophrenia feel that their actions are no longer controlled by themselves. Correspondingly, schizophrenia patients have difficulties in the perceptual distinction between self- and externally produced events (Daprati *et al.*, 1997; Blakemore *et al.*, 2000; Franck *et al.*, 2001; Lindner *et al.*, 2005; Shergill *et al.*, 2005; Heinks-Maldonado *et al.*, 2007).

It has been hypothesized that such failures in the attribution of self-agency to the sensory consequences of actions might result from a deficit within the comparator mechanism (Feinberg, 1978; Frith, 1992; Frith *et al.*, 2000), either related to the generation of inadequate internal predictions and/or to an impaired comparison with the actual sensory afference. According to this idea, patients would be expected to attribute any deviant sensory information (which is no longer compensated by internal prediction) to external sources rather than to themselves—as is the case in delusions

of influence. Yet several studies report that if a spatial or temporal distortion of visual feedback about subjects' hand movements had to be detected, schizophrenia patients expressed a stronger tendency to attribute what they saw to their own actions (Daprati *et al.*, 1997; Fournieret *et al.*, 2001; Franck *et al.*, 2001; Haggard *et al.*, 2003; Knoblich *et al.*, 2004). Such increased thresholds for detecting experimental distortions of self-produced visual information seem neither compatible with the predictions of the comparator model nor with the psychopathology of schizophrenia patients experiencing delusions of influence (Synofzik *et al.*, 2008b; Waters and Badcock, 2008): patients seemingly exhibit an 'over-attribution' (Haggard *et al.*, 2003; Jeannerod and Pacherie, 2004; Jeannerod, 2009) or 'hyper-association' (Haggard *et al.*, 2003) of externally caused sensations to their own agency, whereas the psychopathology of delusions of influence predominantly reflects the exact opposite phenomenon, namely an under-attribution of self-produced afferent information.

In this study, we aimed to dissolve this seeming discrepancy between empirical findings and model predictions. Specifically, we asked whether higher detection thresholds for experimental distortions of self-produced visual information in schizophrenia patients might be due to an increased variability of internal predictions (i.e. self-action estimates that are based on internal action-related information).

We tested our hypotheses in a series of two experiments, in which we modified the visual feedback about subjects' pointing movements in real time. Experiment 1 revealed that the amount of feedback rotation that was detected as deviant from subjects' actual movements was significantly increased in schizophrenia patients and correlated with the strength of their delusions of influence. Experiment 2 assessed both the trial-by-trial variability of visual self-action estimates, as well as their degree of adaptation to a constant feedback-rotation bias. We show an increased variability of these estimates in the patient group that was also observed in interleaved probe trials without visual feedback. In the latter situation, in which self-action estimates solely relied on internal action-related signals, this variability correlated with both patients' delusions of influence and the higher detection thresholds assessed in our first experiment. Finally, the amount of adaptation to the constant feedback rotation was significantly increased in the patient group. We discuss these findings as evidence for a stronger weighting of visual information in schizophrenia patients (as signified by the increased level of adaptation) that is prompted by the reduced reliability of internal predictions about the visual consequences of their actions.

## Materials and methods

We studied schizophrenia patients with delusions of influence and their age-matched controls using previously established psychophysical paradigms that we have described in detail elsewhere (Synofzik et al., 2008a).

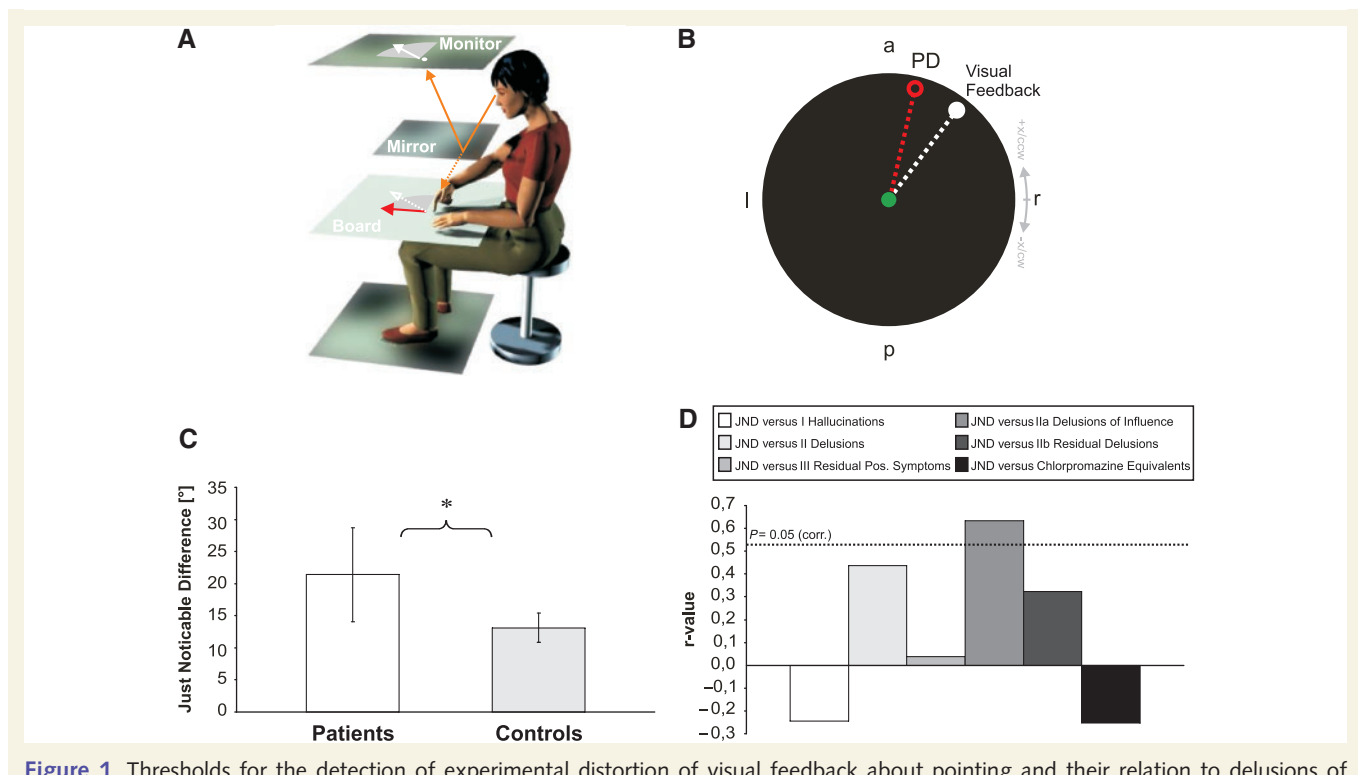
### Subjects

A group of 20 schizophrenia patients [13 male, 7 female; average age =  $28.2 \pm 3.9$  years ( $\pm 95\%$  confidence interval);  $11.3 \pm 0.8$  average years of education (primary + secondary school)] and 20 age-matched healthy control subjects with equivalent levels of education (12 male, 8 female, average age =  $29.8 \pm 5.1$  years;  $11.1 \pm 0.7$  average years of education) participated in this study. All subjects had normal or corrected-to-normal visual acuity and gave their written consent according to the Declaration of Helsinki. Schizophrenia patients were recruited from the Psychiatric University Hospital in Tübingen, Germany. All patients met the Diagnostic and Statistical Manual of Mental Disorders-IV criteria for schizophrenia. Furthermore, all of

them met the criteria for the paranoid subtype of the disorder with predominant delusions and hallucinations. All of the medicated patients were treated with atypical neuroleptics. Hallucinations and delusions were quantified by the Scale for the Assessment of Positive Symptoms (SAPS) (Andreasen, 1984). The mean SAPS was  $57.4 \pm 5.6$  (95% confidence interval). The following subscores were assessed: score I hallucinations,  $11.9 \pm 1.8$ ; score II delusions,  $20 \pm 4.0$ ; score III residual positive symptoms [i.e. (SAPS)—(score I + II)],  $25.6 \pm 3.4$ ; score II-a delusions of influence,  $4.9 \pm 1.2$ ; score II-b residual delusions [i.e. (score II)—(score II-a)],  $15.1 \pm 3.0$ . Refer to Supplementary Table S1 for an overview of all subjects, including information about subjects' sex, age and level of education as well as patients' medication level and overall SAPS score.

### Experimental setup

In all experiments, subjects were required to perform out-and-back pointing movements with their right index finger in a virtual-reality setup (Fig. 1A). Importantly, this setup allowed us to present subjects with a visual cursor that moved in spatio-temporal correspondence



**Figure 1** Thresholds for the detection of experimental distortion of visual feedback about pointing and their relation to delusions of control. (A) Setup: Subjects viewed a virtual image of their finger (white disc) on the feedback monitor via a mirror (solid orange line) while performing pointing movements. This setup allowed subjects to perceive the virtual image in the same plane as their actual finger while the direction of movement could be manipulated (red arrow: movement vector; solid/broken white arrow: actual/perceived visual feedback). (B) Experiment 1: On-line visual feedback (white disc) about pointing (red circle) was either rotated in a counter-clockwise (ccw) or—as in this example—in a clockwise direction (cw) and the size of the rotation angle ( $\alpha$ ) was varied across trials. Dotted lines indicate the pointing movement (red) and the respective visual feedback trajectory (white). PD denotes the actual pointing direction, a, p, l, r denote anterior, posterior, left and right, respectively. The subject's task was to indicate the direction of perceived visual feedback rotation in a two-alternative forced-choice manner (clockwise versus counterclockwise). (C) Just noticeable difference: On average, schizophrenia patients showed a significantly larger just noticeable difference (JND) between the actual and the perceived pointing direction, indicating an impaired ability to detect visual feedback manipulations (means  $\pm 95\%$  confidence intervals, uncorrected). (D) Correlation between psychopathology and the just noticeable difference: The bar plot shows correlation coefficients ( $r$ -values) for the linear correlations between the just noticeable difference and (i) the SAPS sub-scores as well as (ii) patients' medication (chlorpromazine equivalents). The corrected  $P$ -threshold of  $P < 0.05$  is indicated by the dotted line. For further explanation please refer to the main text.

with the tip of their right index finger. Moreover, the cursor trajectory could be manipulated online by applying a spatial rotation around the starting point of the movement, which also served as a fixation spot.

## Experimental design

### Experiment 1

In the first experiment subjects had to perform pointing movements in the table plane, moving as straight and quickly as possible (Fig. 1B). Pointing distance was indicated by a briefly flashed circle (300 ms) that was centred on the starting position of the hand (9° radius). There was no visual target for the pointing movement. Rather, subjects were free to choose any position on the upper right segment of the circle as a goal for their pointing movements (0–90°). The position of the index finger was fed back throughout each trial. Feedback was rotated by varying degrees around the starting point of the movement in a clockwise or counter-clockwise direction. After having completed their pointing movement, subjects had to report the direction of the perceived rotation of visual feedback with respect to their actual movement in a two-alternative forced choice manner: they reported their decision by pressing one of the two buttons with the left index finger (i.e. clockwise) or the left middle finger (i.e. counter-clockwise). The amount of rotation in individual trials was determined by three randomly interleaved staircase procedures (Lieberman and Pentland, 1982). Two procedures targeted the detection thresholds (75% hits) for perceived clockwise and counter-clockwise feedback manipulations, respectively. A third staircase procedure was used to approximate the point of subjective equivalence between perceived movement and visual feedback. At this point subjects responded at chance level. Combined data collected by all three staircase procedures were used to estimate the psychometrical function [by means of a Probit-analysis (McKee *et al.*, 1985)] that describes the likelihood of counter-clockwise decisions as a function of the amount and direction of feedback rotation. Using this function, we determined both subjects' point of subjective equivalence (50% clockwise decisions) and their just noticeable difference of feedback deviation (Supplementary Fig. S1). The just noticeable difference was defined as the mean absolute distance of the two detection thresholds from the point of subjective equivalence.

The just noticeable difference and the point of subjective equivalence were compared on the group level (patients versus matched controls). Group differences in the mean and in the variability of this measure were examined by employing a *t*-test ( $H_0$ : no difference between groups; two-tailed test) and an *F*-test, respectively ( $H_0$ : equal variances). In the following, we will only present the just noticeable differences, since no significant difference emerged for the points of subjective equivalence [patients:  $-15.2 \pm 11.3^\circ$  (95% confidence interval); controls:  $-12.4 \pm 7.5^\circ$ ;  $P > 0.05$ ; also compare supplementary Fig. S2].

### Experiment 2

As in Experiment 1, the basic task of subjects was to carry out pointing movements. After each movement they had to give a perceptual estimate about the action they had performed—i.e. the perceived pointing direction—by placing a mouse-guided cursor into the respective direction using their left hand. This general procedure allowed us to measure subjects' visual estimates about self-action (i.e. the action they have perceived as caused by their own) as expressed by the relative difference between their perceived pointing direction and their 'actual motor behaviour', i.e. their actual pointing direction (PD) (Fig. 2A–C). Self-action estimates were assessed in single trials

and in each of the following, randomly interleaved conditions: 'feedback trials', 'perceptual probe trials' and 'motor probe trials'.

During 'feedback trials', subjects received visual feedback about the peripheral part of their movements. This feedback could induce and maintain adaptation. During the pre-adaptation phase, feedback was kept veridical to get a baseline estimate of the perceived pointing direction. In the 'adaptation built-up phase', we gradually increased feedback rotation angle  $x$  in steps of  $-6^\circ$  (clockwise) over five consecutive trials. Following this build-up, rotation was kept constant at  $-30^\circ$  (Fig. 2A). This post-adaptation phase allowed us to maintain adaptation.

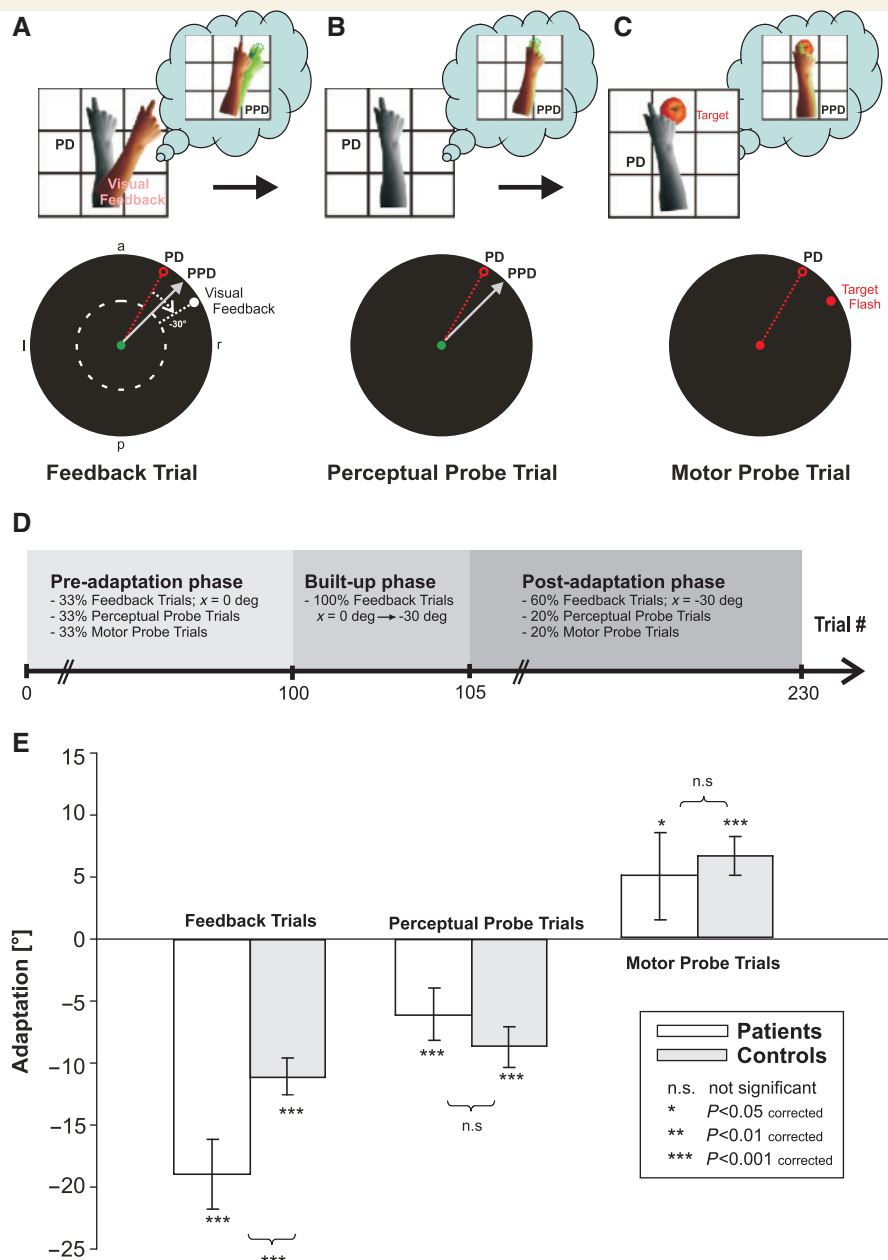
Two types of probe trials were randomly interleaved with the feedback trials: (i) the 'perceptual probe trials' were identical to feedback trials except that no visual feedback was provided at all (Fig. 2B). This condition allowed us to assess the precision of visual self-action estimates (in terms of their variability) and to detect whether the modified visual feedback (provided in feedback trials) was used to update these estimates. Importantly, due to the absence of any visual feedback in perceptual probe trials, here the visual self-action estimate critically depended on internal action-related information, only. (ii) During 'motor probe trials', subjects made a pointing movement towards a visual target that was briefly flashed randomly at one of the four possible positions (90°, 60°, 30° or 0°; Fig. 2C). This condition allowed us to test the accuracy of subjects' motor performance, and—since again no visual feedback was provided—whether subjects would internally update pointing direction in a way that it would account for the new visual consequences.

All aforementioned conditions held the same share of trials in the pre-adaptation phase (33%). In the post-adaptation phase, the share of feedback trials was larger in order to maintain adaptation (60%, perceptual and motor probe trials 20%, each; Fig. 2D). For further details about behavioural monitoring and the calculation of subjects' pointing direction in individual trials please refer to Synofzik *et al.* (2006). Figures 2A–C provide graphical illustrations of the parameters tested in each condition and depict the expected effects of adaptation on each of these parameters for both groups, controls (naturally coloured arms) and patients (green arms, note that an increased variability in the patient group is indicated by the variable perceived movement endpoints in green).

Effects of adaptation on the pointing direction (in motor probe trials) and on the relative perceived pointing direction (in feedback trials and perceptual probe trials) were studied by comparing the differences between the pre-adaptation (trials 1–100) and the post-adaptation phase (trials 106–230). The first 25 trials of the post-adaptation phase were discarded in order to guarantee that adaptation had already been accomplished (Supplementary Fig. S3). Levels of adaptation were compared between groups using *t*-tests ( $H_0$ : no difference between groups; two-tailed test). In order to additionally test for adaptation within each group we performed paired *t*-tests ( $H_0$ : no difference between pre- and post-adaptation phase; two-tailed tests). All resulting *P*-values were Bonferroni-corrected for multiple comparisons.

The trial-by-trial variability of each subjects' behavioural measures was assessed in terms of their standard deviation. We compared the resulting measures of variability for each condition by two-way repeated measures ANOVA with the factor's experimental phase (pre-adaptation phase/post-adaptation phase) and subject group (schizophrenia patients/control group). Since there was no significant interaction between both factors (feedback trials:  $P = 0.30$ ; perceptual probe trials  $P = 0.91$ ; motor probe trials:  $P = 0.81$ ), we used the pooled standard deviation of the pre- and the post-adaptation phase for further analysis. Finally, in order to explore whether the pooled





**Figure 2** Adaptation of self-action estimates and motor performance to a constant visual feedback rotation. (A–C) Paradigm Experiment 2: The top row provides a graphical illustration of each of our three experimental conditions as well as the expected perceptual and motor effects of feedback adaptation on both controls [cf. Synofzik *et al.* (2006); skin coloured arms] and schizophrenia patients [cf. Lindner *et al.* (2005) green arms]: (A) if subjects were constantly provided rotated visual feedback with respect to their actual pointing direction (PD, grey arm), controls would tend to perceive their arm as pointing into the direction of visual feedback. This perceived pointing direction of controls (PPD) is indicated by the skin coloured arm. (B) Even without visual feedback, they would continue to perceive their arm as pointing into the same visual direction (as in A) since they would have ‘internalized’ the new visual consequences associated with this action. (C) Finally, if asked to reach for a specific visual target (apple) without visual feedback, controls would reach in a direction opposite to the feedback rotation in order to account for the altered visual consequences of their movement. In the case of schizophrenia patients we hypothesized that—due to imprecise internal predictions—these patients would over-rely on visual feedback about self-action and thus perceive their arm as even further rotated into the direction of the visual feedback manipulation (A, green arm). In addition, imprecise internal predictions should cause a higher variability of the visual self-action estimates (A and B, green dots indicate variably perceived movement directions). Finally, we did not expect any alteration in patients’ motor performance (C). The bottom row of panels A–C depicts the three different experimental conditions that we used to obtain the aforementioned measures. For a complete description of these conditions please refer to the methods section. Exemplary pointing and a rotated feedback trajectory are shown by the dotted red lines and the dotted white line, respectively. Exemplary perceived pointing directions are indicated by the solid grey arrows. The dashed circle in (A) indicates that the first half of subjects’

Continued

variability of the visual self-action estimates in perceptual probe trials could account for the detection thresholds in Experiment 1 (i.e. the just noticeable differences), we performed a linear correlation analysis between the two measures.

## Correlation of behavioural measures and patients' psychopathology

Within the group of schizophrenia patients, we correlated specific aspects of our patients' psychopathology—as assessed by the SAPS and its sub-scores—with the task-specific behavioural measures of Experiments 1 and 2. Such a within-group analysis has the advantage that non-specific effects common to the patient group as a whole (e.g. caused by hospitalization, etc.) can be ruled out. Specifically, we correlated the SAPS and its sub-scores (for definition see 'Subjects' section) with each of the following behavioural measures: just noticeable difference (Experiment 1), adaptation in feedback trials, perceptual probe trials and motor probe trials as well as the pooled standard deviations of these behavioural measures (Experiment 2). In addition, we included subjects' level of medication [expressed as Chlorpromazine equivalent; calculated according to Woods (2003) as an additional explanatory variable in our analysis. This analysis did not reveal a significant influence of the level of medication on any of the behavioural measures under consideration. All reported *P*-values were Bonferroni-corrected for multiple comparisons within each measure.

## Results

### Experiment 1

Experiment 1 tested (i) whether schizophrenia patients, in agreement with previous studies, would exhibit larger detection thresholds for feedback manipulations (as assessed by the just noticeable difference); and (ii) whether these thresholds would be larger, the stronger the patients' delusions of influence.

In fact, patients showed significantly increased just noticeable differences (patients: 21.4° versus controls: 13.1°;  $P < 0.05$ , *t*-test; Fig. 1C) and also the variability of the just noticeable difference across subjects was significantly higher in the patient group ( $P < 0.001$ , *F*-test). The larger just noticeable differences of the patient group were also reflected in their individual psychometrical functions, which demonstrated more gentle slopes as compared with those of the control group (Supplementary Fig. S1).

Importantly, the size of patients' just noticeable difference correlated significantly and selectively with the SAPS sub-score

assessing their delusions of influence [sub-score IIa; *r*-value = 0.63;  $P < 0.05$  (corrected)]: the stronger these delusions, the higher the detection thresholds. Neither hallucination nor any residual positive symptoms or residual delusions showed any significant correlation with the just noticeable difference (Fig. 1D).

### Experiment 2

Experiment 2 engaged a perceptual adaptation paradigm, which required subjects to estimate the perception of their own actions in the presence of constantly rotated visual feedback (feedback trials). In addition, we assessed subjects' self-action estimates in randomly interleaved perceptual probe trials, in which no visual feedback was provided. We also monitored motor performance in interleaved trials that obliged subjects to point towards explicit visual targets in the absence of visual feedback (motor probe trials).

When visual feedback was presented constantly rotated by 30° in the post-adaptation phase of Experiment 2, both groups showed a significant shift of their perceived pointing direction in feedback trials: as compared to the pre-adaptation phase, i.e. the baseline epoch with veridical visual feedback, perceived pointing was rotated into the direction of adaptation. Yet, the shift of this perceptual estimate was significantly stronger and almost two times larger in schizophrenia patients than in controls (−18.9° versus −11°;  $P < 0.001$ , *t*-test; Fig. 2E; see Supplementary Fig. S3 for individual examples of each group). In other words, the amount of external feedback bias that schizophrenia patients attributed to their own agency was 'exaggerated'.

In interleaved perceptual probe trials, in which no visual feedback was provided, both groups showed a highly significant adaptation ( $P < 0.001$ ; *t*-test) of comparable amount (−6.1° versus −8.6°;  $P > 0.05$ , *t*-test; Fig. 2E). Likewise, both groups exhibited a comparable compensatory adjustment of pointing in motor probe trials despite the lack of visual feedback (5.0° versus 6.6°;  $P > 0.05$ ; Fig. 2E).

In the next step, we assessed the trial-by-trial variability of each subject's behavioural measures in terms of their standard deviation and compared the resulting variabilities between groups. Schizophrenia patients showed a significantly larger variability of their perceptual estimates in both feedback trials and perceptual probe trials (feedback trial: 15° versus 10° SD; PCT: 14° versus 10° SD;  $P < 0.05$ , *t*-test), while the variability of their motor performance was the same as that of controls (MCT: 17° versus 13° SD;  $P > 0.05$ ; *t*-test). In order to explore whether the increased

#### Figure 2 Continued.

visual movement trajectory was occluded to avoid any online-corrections of pointing. An explicit pointing target (red circle) was only flashed in motor probe trials (C), while in the remaining conditions (A and B) subjects were free to point in any freely chosen direction between subjective 0° (*r*) and 90° (*a*, anterior). No visual feedback was provided in probe trials (B and C). (D) Time-line of Experiment 2: This illustration indicates the share of each experimental condition and also specifies *x*, namely the angle of visual feedback rotation, for each of the different stages of adaptation. (E) Group results: Both groups showed a significant, adaptation-induced shift of their perceived pointing direction into the direction of feedback rotation. Schizophrenia patients thereby expressed significantly higher levels of adaptation as long as visual feedback was present (feedback trials). In the absence of visual feedback, the adaptation of the perceived pointing direction was significant in both groups and of a comparable amount (perceptual probe trials). Moreover, both groups significantly adjusted their motor behaviour by a comparable amount (motor probe trials; figure-conventions as in Fig. 1).

variability of the visual self-action estimates in perceptual probe trials could also account for patients' higher detection thresholds in Experiment 1, we performed a linear correlation analysis between the two measures in both groups: while there was a significant linear correlation between patients' just noticeable difference and the variability of the self-action estimates in perceptual probe trials ( $r$ -value = 0.38;  $P < 0.05$ ), such correlation was absent in the group of controls ( $r$ -value = 0.10;  $P > 0.05$ ). This highlights a specific inter-relation of the two measures in the patient group.

Finally, we correlated specific aspects of our patients' psychopathology and the levels of medication with the task-specific behavioural measures. In none of the three experimental conditions the amount of adaptation correlated with medication, the SAPS or one of its sub-scores. However, the variability of the

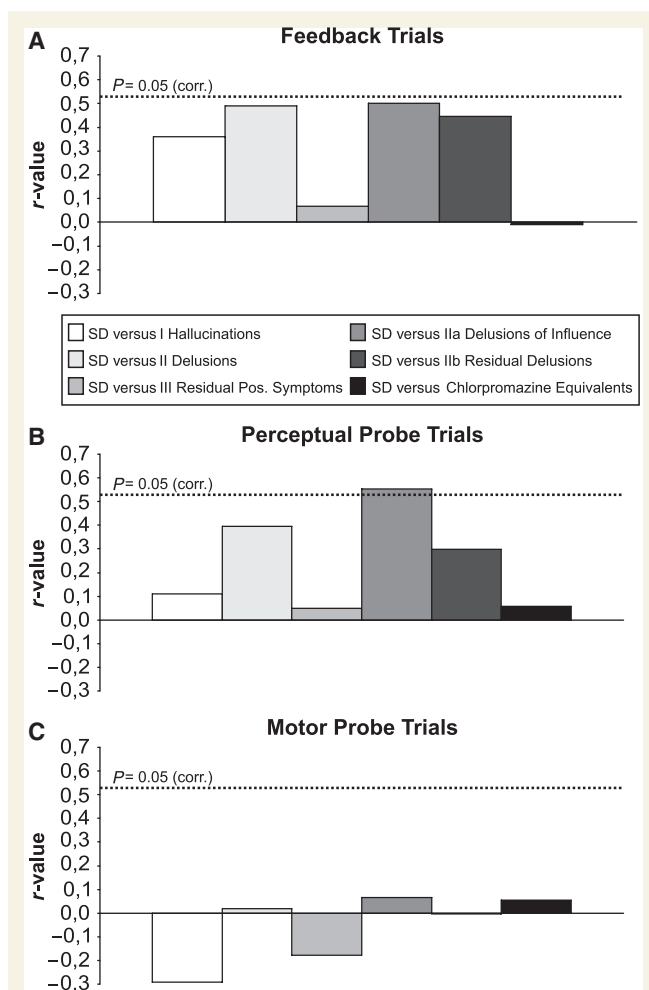
perceptual estimate in perceptual probe trials correlated specifically with sub-score IIa [ $r$ -value = 0.57;  $P < 0.05$  (corrected)], but not with any other of the relevant sub-scores (Fig. 3B). In other words, the higher the score for delusions of influence, the higher the variability in predicting the visual consequences of one's own actions in perceptual probe trials. A similar trend emerged in feedback trials. Yet, the correlation between the variability of patients' self-action estimates and sub-score II-a failed to reach the statistical threshold [Fig. 3A;  $r$ -value = 0.50;  $P > 0.05$  (corrected)]. In contrast, the variability of motor performance in motor probe trials did not correlate with any of the SAPS sub-scores (Fig. 3C). These results indicate a highly specific correlation between delusions of influence—but not any other aspect of patient's psychopathology—and the variability in the self-attribution of action in the absence of any visual feedback, i.e. in situations where visual self-action estimates are solely based on internal action-related information.

## Discussion

This study demonstrates that the ability to attribute sensory events correctly to their actions is specifically impaired in schizophrenia patients experiencing delusions of influence: (i) patients were impaired in detecting experimental distortions of visual feedback about their own pointing movements; (ii) patients exhibited increased variability when estimating the visual consequences of their own behaviour in the absence of visual feedback (and during its presence); (iii) both deficits (i and ii) correlated with each other and, importantly, with the strength of delusions of influence patients experienced; and (iv) schizophrenia patients showed increased adaptation of their self-action estimates when the visual feedback about subjects' pointing movement was rotated by  $-30^\circ$ . We interpret these results as support for the notion that deficits in a comparator mechanism contribute to disorders of agency in schizophrenia patients (Frith, 1992; Frith et al., 2000). Specifically, as will be discussed, we assume that delusions of influence are based on imprecise internal predictions about the sensory consequences of one's own actions (ii and iii). Moreover, we propose that imprecise internal predictions could prompt schizophrenia patients to rely more strongly on additional external cues about self-action (iv).

Experiment 1 allowed us to confirm previous studies that demonstrated larger detection thresholds in detection tasks where visual feedback about a subject's own actions was manipulated in the spatial or temporal domain (Daprati et al., 1997; Fournier et al., 2001; Franck et al., 2001; Knoblich et al., 2004). Importantly, however, this is the first experiment to establish a direct correlation between delusions of influence and increased detection thresholds (here just noticeable differences), seemingly reflecting an over-attribution of sensory feedback from external sources to one's own agency.

As pointed out in detail in the Introduction, such putative over-attributions are not only inconsistent with the psychopathology of delusions of influence, since here patients usually under-attribute self-agency to the sensory consequences of their own actions, i.e. they wrongly assign authorship to external agents. They are



**Figure 3** Correlation of patient's psychopathology with the variability of the behavioural measures. This figure summarizes the correlation coefficients ( $r$ -values) that were obtained by the linear correlation analyses calculated between the variability (i.e. the standard deviation, SD) of the behavioural measures in Experiment 2 and (i) different sub-scores of the SAPS as well as (ii) patient's medication (chlorpromazine equivalents). The respective correlation coefficients are separately shown for feedback trials (A), perceptual probe trials (B) and motor probe trials (C). Corrected  $P$ -thresholds of  $P < 0.05$  are indicated by the dotted lines.

also at odds with the predictions of the comparator model: if patients were impaired in generating adequate internal predictions that match the sensory consequences of their actions (Frith, 2005), they should misattribute self-produced sensory information to external sources. Thus, alternative interpretations have been put forward to explain these putative over-attributions, such as attentional or visual deficits or a more general impairment in action attribution behaviour (Fournier *et al.*, 2001; Delevoeye-Turrell *et al.*, 2003; Allen *et al.*, 2004; Synofzik *et al.*, 2008b; Waters and Badcock, 2008).

However, as we recently suggested (Lindner *et al.*, 2005), deficits in the comparator might very well be able to explain patients' increased thresholds for detecting external manipulations of self-produced sensory feedback. Imprecise predictions could prompt the perceptual system to rely more strongly on external (in this case visual) action-related information in order to receive a more reliable account of one's own actions: subjects might have relied on the fact that the cursor was a visual representation of their own fingertip and used this visual ownership information (Tsakiris and Haggard, 2005; Synofzik *et al.*, 2008c) as an 'external agency cue'. Besides, internal predictions could *per se* account for patients' increased detection thresholds: imprecise predictions would lead to incomplete accounting for the self-produced sensory information in single trials, while the unexplained part of this sensory information would be attributed to external sources (as in delusions of influence). In both cases, the resulting psychometrical function between the true external distortion of the sensory feedback about self-action (here clockwise or counter-clockwise rotations) and the perceived distortion (clockwise or counter clockwise, respectively) would smear out due to a stronger weighting of the inconsistent visual feedback and/or due to an increased trial-by-trial variability of internal predictions. In each case, the just noticeable difference will increase accordingly (Supplementary Fig. S1).

Experiment 2 served to scrutinize the putative relationship between imprecise internal predictions and delusions of influence further. As will be pointed out in the following, our paradigm allowed us to assess both (i) the accuracy of internal predictions on the one hand and (ii) the weighing of internal and external information about subjects' pointing movement on the other.

## Accuracy of internal predictions

The accuracy of internal predictions was estimated based on the trial-by-trial variability of the visual self-action estimates subjects provided in the perceptual probe trials: since in these trials no visual feedback about subjects' pointing movements was provided and since these movements were internally generated, i.e. not guided by any external visual goal, each visual estimate of the perceived pointing direction always critically depended on internal cues related to the actual pointing movement performed. Such cues could be efference copies of motor commands (von Holst and Mittelstaedt, 1950), corollary discharge (Sperry, 1950; Crapse and Sommer, 2008a) and/or proprioceptive movement information (Bell, 2001) (for a complete discussion see Synofzik *et al.*, 2006). In any of these cases, internal cues are the sole source of information on which the visual self-action estimates could be based on. We thus assume that this single-trial measure

captures a prediction of the visual consequences of self-action that builds on internal information, i.e. it reflects an internal prediction. We estimated the trial-by-trial variability of the perceptual estimates in perceptual probe trials in terms of their standard deviation. The standard deviation was significantly higher in schizophrenia patients and, importantly, correlated with delusions of influence. In other words, the more imprecise the estimate of internal predictions, the stronger were the delusions of influence that patients experienced. The fact that schizophrenia patients did not reveal a higher variability in internally guided movements (pointing in the absence of visual feedback in motor probe trials) and that variability did not correlate with any other aspect of our patients' psychopathology or level of medication underlines the specificity of this finding: it not only rules out unspecific disease effects and disapproves abovementioned more general interpretations (i.e. general attentional or visual deficits or a general impairment in action attribution behaviour), but further substantiates the specificity of the comparator theory of agency: according to this theory prediction deficits should occur only in those patients experiencing delusions of influence. Moreover, since delusions of influence are deficits on the perceptual level, not on the motor level, they should primarily occur due to deficits in predictions subserving the perception of one's actions but not necessarily due to deficits in motor performance—as demonstrated here (for a more detailed discussion see Synofzik *et al.*, 2008b).

In order to test whether imprecise internal predictions could explain patients' higher detection thresholds in Experiment 1, we performed a linear correlation analysis between the latter measures (i.e. the just noticeable differences) and the pooled standard deviation of subjects' self-action estimates in perceptual probe trials of Experiment 2. The specific, significant correlation in the patient group clearly speaks in favour of such interdependence. It yet has to be determined whether the increased detection thresholds in the patient group could be explained by imprecise internal predictions only, or by an additional re-weighting of internal and external cues about self-action. Indirect support for the latter assumption stems from subjects' level of adaptation in Experiment 2.

## Weighing of internal and external information about self-action

The constant rotation of visual feedback about subjects' pointing movement in Experiment 2 led to a modification of visual self-action estimates in both groups. Specifically, in both feedback trials and perceptual probe trials, perceptual adaptation was significantly different from baseline. The fact that both groups showed an identical degree of adaptation in the absence of visual feedback (perceptual probe trials) thereby disproves the possibility of 'a general unavailability' or inaccessibility of internal predictions in schizophrenia patients. Moreover, it demonstrates that subjects integrated visual information about self-action in order to update their internal predictions (Haarmeier *et al.*, 2001; Synofzik *et al.*, 2006). Yet, if visual cues about self-action were provided (feedback trials), patients' self-action estimates seemed to rely more strongly on such external feedback. This



was evident from the level of adaptation in feedback trials, which was almost doubled when compared to the level reached by the control group. This difference in patients' self-action estimates in feedback trials might derive from an integration of internal and external cues about self-action weighted by their relative reliability for a given context. This notion is borrowed from the framework of optimal cue integration in which different sources of information are added according to their relative reliability (Ernst and Banks, 2002; Ernst and Bulthoff, 2004; Kording and Wolpert, 2004; Synofzik et al., 2009). Here, the reliability of patients' internal predictions (estimated by the inverse of the squared pooled standard deviation of the perceptual self-action estimates in perceptual probe trials) was about half as compared to that of healthy controls (0.005 versus 0.01,  $1/\text{deg}^2$ , respectively). Accordingly, as compared to healthy controls, schizophrenia patients should give less weight to internal predictions thereby increasing the relative weight of alternative (visual) cues about self-action. This relative weighting is reflected by the degree of adaptation of the self-action estimates in feedback trials (relative to the absolute visual feedback bias of  $-30^\circ$ ). Here, the average degree of adaptation was 37% ( $-11.0^\circ$ ) in controls, whereas it was about two times larger in schizophrenia patients (63%;  $-18.9^\circ$ ), thus confirming our prediction.

In summary, our results support the notion of a dysfunction of the comparator mechanism in schizophrenia (Frith, 1992; Frith et al., 2000; Lindner et al., 2005). This dysfunction relates to an increased variability of internal predictions about the sensory consequences of self-action, which—as expected—correlates specifically with patients' delusions of influence. Yet, apart from internal predictions, additional external information about self-action contributed to subjects' self-agency judgements. Our results thereby support the notion that the weighting of internal and external cues about self-action could depend on the reliability of internal predictions [similar to the framework of optimal cue integration (Fletcher and Frith, 2009; Synofzik et al., 2009)]. Specifically, imprecise predictions might have prompted schizophrenia patients to rely more strongly on external cues about self-action (in this case vision). This change in strategy could also explain the episodic nature of delusions of influence: in many cases, the stronger weighting of external cues could help patients to avoid a misattribution of agency for self-produced sensory events due to imprecise internal predictions. However, as a consequence, they would be at constant risk of becoming 'a slave to every environmental influence' (Frith, 1994; p. 151): schizophrenia patients might over-attribute external events to their own agency whenever stronger weighted external agency cues are in fact not veridical and misleading (as in Experiment 1). Conversely, if external cues are temporarily not attended or unavailable, patients might fail to attribute self-produced sensory events to their own agency and assume external causal forces (as is the case in delusions of influence). Of course, for forming out specific delusional beliefs, as observed in schizophrenia patients, these rather basic impairments have to be complemented by additional changes in a patient's belief formation process (Davies et al., 2001; Synofzik et al., 2008b). However, our study might have identified the most basic key factors triggering

both patients' unusual perceptions and their delusions (Fletcher and Frith, 2009).

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## Supplementary material

Supplementary material is available at *Brain* online.

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