Schizotypal personality traits and prediction of one’s own movements in motor control: What causes an abnormal sense of agency?

Tomohisa Asai *, Eriko Sugimori, Yoshihiko Tanno

Department of Cognitive and Behavioral Science, Graduate School of Arts and Sciences, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153–8902, Japan

**ABSTRACT**

Background. Positive schizophrenic symptoms, especially passivity phenomena, including auditory hallucinations, may be caused by an abnormal sense of agency, which people with schizotypal personality traits also tend to exhibit. A sense of agency asserts that it is oneself who is causing or generating an action. It is possible that this abnormal sense of self-agency is attributable to the abnormal prediction of one’s own movements in motor control. Method. We conducted an experiment using the “disappeared cursor” paradigm in which non-clinical, healthy participants were required to click on a target using an invisible mouse cursor. Prediction error was defined as the distance between the target and the click point. Results. The results showed that schizotypal personality traits, but not depressive or anxious traits, were correlated with deficits in predicting movements of the subjects’ left hand. In particular, auditory hallucination proneness had the strongest relationship with movement prediction error. Conclusions. This finding is in accordance with the idea that passivity phenomena or proneness may be caused by the abnormal prediction of one’s own actions or movements.

1. Introduction

1.1. Schizophrenia and Schizotypal personality traits

Schizophrenia patients are impaired in perceptual as well as cognitive functions. In the past dozen years, several theoretical models of schizophrenia symptoms have been proposed, often inspired by advances in cognitive neuroscience. It was recently suggested that these models of schizophrenia may also apply to schizotypal personality traits (schizotypy). For example, Cyhlarova and Claridge (2005) indicated that schizotypal people, identified by questionnaires or semi-structured interviews, might have a predisposition to schizophrenia. Although schizotypal people might experience schizophrenic-like experiences, including auditory hallucinations, many can live normal lives. The traits of schizophrenia are generally considered to span a continuum. However, controversy remains regarding whether this continuum is quasi-dimensional, applying only to people with schizophrenia and schizotypy, or fully dimensional, applying to all people (Claridge & Davis, 2003). By the latter perspective, all people have schizotypal personality traits to some extent, and those who have strong schizotypal traits might develop schizophrenia. Correlations between cognitive dysfunctions and schizotypal scores in the general population (e.g., Lenzenweger & Maher, 2002) provide support for the fully dimensional model of schizotypy. Our study was also conducted from the viewpoint of the fully dimensional model.
Individual differences in schizotypal personality have commonly been explored as a means of examining the nature and structure of schizophrenia symptoms. Research on schizotypal personality in the general population may provide a particular opportunity to study the biological and cognitive markers of vulnerability to schizophrenia without the confounding effects of long term hospitalization, medication and severe psychotic symptoms (Raine & Lencz, 1995). Relatives of schizophrenia patients score significantly higher on measures of schizotypal personality, which suggests that within the spectrum of schizophrenia disorders there is a range in which schizotypal traits may be expressed and that this range is at least partly genetic (Kremen, Faraone, Toomey, Seidman & Tsuang, 1998; Lenzenweger, 2006; Plated & Gallup, 2002).

Many people with schizophrenia describe a sense of passivity to their experiences, in that their actions, thoughts, or emotions are created for them by some external agent rather than by their own will. These symptoms are included among Schneider’s first-rank symptoms for schizophrenia (Mellors, 1970; Schneider, 1959). In most cases, the actions carried out when people feel that they are being controlled by alien forces are not discrepant with their intentions (Frith, Blakemore & Wolpert, 2000a, 2000b). In other words, people with schizophrenia have an abnormal sense of agency, which is the feeling of causing our own actions (Gallagher, 2000). Phenomena such as delusions of control, auditory hallucinations, and thought insertion may all be caused by abnormal agency (Frith et al., 2000a; Gallagher, 2004; Lindner, Their, Kircher, Haarmeier & Leube, 2005). For example, auditory hallucination might be one’s own speech (McGuigan, 1966). The activation of Broca’s area, which can produce but does not listen to speech, has been found in people having auditory hallucinations (McGuire, Shah & Murray, 1993). Therefore, these people might produce speech, but not think that it is they who spoke. As a result, they may hear their own voices as the voices of others.

The schizophrenic abnormal sense of agency has been shown empirically. Two studies reported that when required to make judgments about the origin of actions based upon biased feedback, people with schizophrenia were more likely than normal controls to judge that they had originated the action (Daprat et al., 1997; Franck et al., 2001). Moreover, Asai and Tanno (2007a, 2008) reported that highly schizotypal people also have an abnormal sense of agency, applying the paradigms of Franck et al. (2001) and Sato and Yasuda (2005).

1.2. The computational model of motor control and the sense of agency

The forward model, which is part of the computational model of motor control (Wolpert, Ghahramani & Jordan, 1995), explains the neuropsychological mechanism of the sense of agency (Frith et al., 2000b; Wolpert, 1997). This model includes two information processing pathways, the action-predictive and the executive pathway: the former for the action planning, the latter for the action execution (Miall & Wolpert, 1996; Schmidt, 1988). It can be applied in several ways, including the differentiation of self-produced sensations from externally generated sensations (Miall & Wolpert, 1996). Prediction of the actual outcome of motor command can be compared with the desired outcome (forward dynamic model). This comparison enables rapid error correction before sensory feedback is available (Greenwald, 1970). When a movement is made, an efference copy of the motor command is used to make a prediction of the sensory consequences of the movement (forward output model). The sensory prediction can then be compared with the actual sensory feedback from the movement. This prediction can be used to anticipate and cancel the sensory effects of movement, as in the case during eye movements (Helmholtz, 1867). More importantly, this prediction can be also used to attenuate the sensory effect of self-generated movement and thereby enables differentiating self-produced sensation from externally generated sensations. Self-produced sensations can be correctly predicted from motor commands. As a result, there will be little or no sensory discrepancy resulting from the comparison between the predicted and actual sensory feedback. This accurate prediction can be used to attenuate the sensory effects of self-produced movement. In contrast, externally generated sensations are not associated with any efference copy and cannot be predicted by the forward model. As a result this comparison will produce a higher level of sensory discrepancy. As the discrepancy between the predicted and actual sensations increases, so does the likelihood that the sensation is externally produced (Sato & Yasuda, 2005). In this way, the forward model can differentiate self-produced sensations from externally generated sensations and generate a sense of agency (Fig. 1; Blakemore & Frith, 2003; Blakemore, Wolpert & Frith, 2002; Frith et al., 2000b; Wolpert, 1997; Wolpert et al., 1995). According to (Miall and Wolpert, 1996) review, the circuit linking the ventral premotor cortex (F5), the PF part of the posterior parietal cortex (PPC), and the superior temporal sulcus (STS) may act as an output model, along with the cerebellum, to predict movement outcome. Further, the extrastriate body area (EBA), which might support the disentangling of one’s own behavior from that of another (David et al., 2007), may act as comparator to generate a sense of agency.

Frith et al. (2000a), (2000b) and Blakemore and colleagues (2002) suggested that the abnormal sense of agency experienced by people with schizophrenia might be caused by an abnormal prediction system in their motor control or forward model. They are aware that an action matches an intention, but have no awareness of initiating the action or of its predicted consequence. That is, the action executive pathway or actual sensory feedback may still produce a sense of self-ownership (“I am moving”) but the sense of agency is compromised (“I am not causing the movement”), even if the actual movement matches the intended movement (Gallagher, 2000). Indeed, Carnahan, Aguilar, Malla, and Norman (1997) showed that people with schizophrenia demonstrated abnormal movement planning, which is associated with action prediction, although they have normal movement execution.

How does the level of the abnormal prediction pathway in the forward model lead to an abnormal sense of agency? Frith (2005) suggested at least three possibilities: the abnormal forward dynamic model, the forward output model, and the comparator (Fig. 1). Whichever the abnormalities that might cause an abnormal sense of agency, the clinical effec-
The effectiveness of drugs is strongly related to the blocking of dopamine receptors (Seeman, Lee, Chau-Wong & Wong, 1976). An abnormal comparator may be related to the role of dopamine in broadcasting prediction errors (Schultz & Dickinson, 2000) and in novelty detection (Lisman & Otmakhova, 2001), which may also apply to the processing of mismatches between the output of the forward and subsequent sensory feedback (Frith, 2005). The evidence that schizophrenic patients conform to the abnormal forward output model has increased. It has been claimed that schizophrenia may be a disorder of the corollary discharge systems (Blakemore, Rees, & Frith, 1998; Feinberg & Guazzelli, 1999; Ford & Mathalon, 2004, 2005; Ford et al., 2001; Shergill, Samson, Bays, Frith & Wolpert, 2005), which are emphasized in the forward output model.

However, because the comparator and forward output model receive information from the forward dynamic model, those studies may also suggest the validity of the abnormal forward dynamic model. Some studies have suggested that people with schizophrenia exhibit the abnormal forward dynamic model, which predicts the next state of our body when given motor commands. Frith and Done (1988) showed that schizophrenics are unable to rapidly correct their arm movements. The forward dynamic model makes this “online” correction of movement possible (Miall & Wolpert, 1996). Lenzenweger and Maher (2002) showed that highly schizotypal people show abnormalities in line drawing tasks, which suggests abnormal motor control. It is possible that the abnormal forward dynamic model leads to the abnormal motor control in high schizotypes. Although these studies may suggest that schizophrenic symptoms or personalities are related to abnormalities in movement prediction, the relationships between them remain unclear. Thus, we need more suitable experimental methods to examine the relationships between schizotypal features and movement prediction. Ogawa, Inui, and Sugio (2006) tried to determine which area of the brain is most relevant in the prediction of one’s own movements using fMRI. In that study, the cursor was moved on the PC screen by participants moving the mouse device. Under the condition of predicting one’s own movements, they traced the target with an invisible cursor.

1.3. The current study

Applying the paradigm of Lenzenweger and Maher (2002) and Ogawa et al. (2006), we examined the relationship between schizotypal personality traits in people from the general population and the prediction of one’s own reaching movements under a no-visual-feedback condition. In addition to scales separately measuring each schizotypal trait (Lenzenweger & Maher, 2002), we also used the comprehensive scale for schizotypy. By using both types of scale, we could clarify which aspect of schizotypy is related to the abnormal prediction of self-movement. Our study involved visuo-motor transformations for which the output could only be perceived visually. Thus, in the experimental setting, the participants could only use proprioceptive feedback and had to access their internal model to control their arms in a predictive way (open-loop control; Ogawa et al., 2006). In contrast, when visual feedback is available, visuo-motor transformation can generally be mastered so that there is no need to access an internal model and visual closed-loop control is available (Heuer & Hegele, 2008). We hypothesized that highly schizotypal people, especially those with positive schizotypy (which includes auditory hallucination proneness), exhibit more errors in predicting their own arm movements. Moreover, this paradigm also allows us to examine how schizotypal people predict their own movements. In the case of auditory hallucinations, for example, one’s own speech may be an important factor (McGuigan, 1966), in that the hallucinations may be caused by underestimating speech. Thus, we hypothesized that positive schizotypy, including passivity phenomena-like experiences, are related to the underestimation of their movements by schizotypal individuals.

Focusing on non-clinical healthy schizotypal people can be an effective way of studying the process of schizophrenia while avoiding the problems that can arise when conducting experiments in patients with schizophrenia (Williams & Beech, 1997). Moreover, it may also be effective in earlier intervention and in preventing the incidence of the disease.
2. Method

2.1. Participants

A total of 41 university students (aged 18–27 years, mean = 19.3; 21 men, 20 women) participated in the experiment and questionnaire. They were recruited from an introductory psychology class participant pool. We sent an e-mail describing the experiment and the questionnaire, to which interested participants responded voluntarily. None had histories of mental illness and all were familiar with manipulating a computer mouse using their right hand. We obtained written informed consent from all of the participants before conducting the experiment.

2.2. Experiment

2.2.1. Apparatus

The experiment was conducted in a silent, dark room. The visual stimuli were created and the experiments conducted using MATLAB (MathWorks, Natick, MA, USA) and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The cursor on the screen (1024 × 1280 pixels) moved in response to movements of the wireless mouse device. The speed of the cursor was synchronized with the mouse moving (e.g., when they moved the mouse device 10 cm, the cursor also moved 10 cm on the screen.) The cursor moved from the center of the screen in every trial (Fig. 2).

2.2.2. Procedure

Participants were required to move the mouse device in a straight line to one of the four targets and then click the mouse. The targets were small squares (2 × 2 pixels) at the corners of the screen. Their x–y coordinates ranged from 100 to 300 pixels (e.g., if the target was in the first quadrant, it could be at the point from 100 × 100 to 300 × 300). The instant they started moving the mouse, the cursor disappeared. This meant that they had to reach the target without visual feedback, predicting their arm movements. After their clicks, the cursor appeared again so that they could view their actual errors. Their x–y coordinates and time durations from mouse moving to click were recorded. They participated in two blocks: the right-hand block, in which they moved the mouse device with their right hand; and the left-hand block, in which they moved the mouse device with their left hand. The order was counterbalanced among participants. In each block, 40 trials (4 directions × 10 times) were conducted in random order.

2.2.3. Data analysis

The experiments yielded three measures: duration time of movements, prediction error value, and underestimation of movement values.

For the prediction error value, MATLAB determined the Euclidean distance between the target and the point at which participants clicked for each trial. We calculated the root mean square (RMS; see Formula 1a) for each participant and for the right- or left-hand block and calculated the averaged RMS of four directions, which defines the error score for participants'
predictions of their own movements. The RMS considers not only the mean value but also the variance (See Formula 1b). This means that if someone moves the mouse imprecisely, the RMS value increases.

\[
x_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots + x_N^2}{N}}
\]

(Formula 1a)

\[
x_{\text{rms}}^2 = \bar{x}^2 + \sigma^2
\]

(Formula 1b)

\[x: \text{the distance between the target and the click point}
\]
\[N: \text{number of trials}
\]
\[\bar{x}(\text{bar}): \text{mean of } x
\]
\[\sigma: \text{standard deviation}
\]

For the underestimation of movement values, the Euclidean distance between the target and the clicked point was transformed, so that negative values indicated undershoots, and positive values recorded overshoots of the target (Lenhard & Hoffmann, 2007). For example, if the \(x-y\) coordinates of the target were 100/100, click points within a 100-radius circle would indicate undershooting. We calculated the averaged value for each participant and hand block. Participants who underestimated their movements would overshoot the target because their hand would move more than expected. Thus, positive averaged values indicated that participants underestimated their movements.

2.3. Questionnaire

After the participants finished the experiment, they received a battery of questionnaires and were required to submit them within a week. We assigned a random number to each participant. The data from the questionnaires were cross-checked with experimental data using this random assigned number. To avoid experimenter effects, we asked them to fill in the questionnaires while alone at home. The questionnaire battery included the following questionnaires. All of them have been demonstrated to show good reliability and validity.

1. **Handedness**: The Annett Hand Preference Questionnaire (AHPQ; Annett, 1970) is generally regarded as a reliable self-report measure of handedness. In their responses, participants were required to indicate whether they use their right, left, or either hand for six primary and six non-primary common actions. According to the Annett (1985) revised classification system, we scored participants from one, indicating fully right-handed, to seven, indicating fully left-handed.

2. **Depression**: The Beck Depression Inventory (BDI; Beck, Ward, Mendelson, Mock, & Erbaugh, 1961) is a well-known self-report 21-item questionnaire measuring depressive tendencies. In their responses, participants chose the most appropriate option from a series of statements.

3. **Anxiety**: The State-Trait Anxiety Inventory (STAI-T; Spielberger, Gorsuch, & Lushene, 1970) is a well-known self-report 20-item questionnaire with responses based on a 4-point Likert metric system measuring anxiety traits.

4. **Schizotypy**: The Oxford–Liverpool Inventory of Feelings and Experiences (O–LIFE; Mason, Claridge, & Jackson, 1995) is a 104-item true–false self-report questionnaire measuring comprehensive schizotypal personality traits. It has four subscales: Unusual Experiences (UnEx), Introvertive Anhedonia (InAn), Cognitive Disorganization (CoDi), and Impulsive Non-conformity (ImNo).

5. **Positive schizotypy**: The Oxford Schizotypal Personality Scale (STA; Claridge & Broks, 1984; Cyhlarova & Claridge, 2005; Gregory, Claridge, Clark, & Taylor, 2003) is a 37-item true–false self-report questionnaire based on the DSM-III diagnostic criteria for schizotypal personality disorder. It measures schizotypal traits, especially perceptual aberrations that are analogous to positive symptoms, including auditory hallucinations, thought insertions, and delusions of control.

6. **Auditory hallucination proneness**: The Auditory Hallucination Experience Scale (AHES; Onari, 1998; Takeshita, 2003; Tanno, Ishigaki, & Morimoto, 1998) is a revised version for healthy people based on the Launay Slade Hallucination Scale (LSHS; Launay & Slade, 1981; Morrison, Wells, & Nothard, 2000; Waters, Badcock, & Maybery, 2003). AHES is a self-report 40-item questionnaire with responses based on a 5-point Likert metric system (0–4) measuring frequency of auditory hallucination-like experiences (e.g., “I heard someone’s voice, but nobody was actually around”). The scores for this scale range from 0 to 160.

In all questionnaires except for the AHPQ, higher scores meant a stronger tendency.

2.4. Statistical analysis

In our analysis, we followed Lenzenweger and Maher (2002) study. Associations between the schizotypy indicators and the dependent variables concerning experimental performance (one’s own movement prediction error (RMS)) were examined using Pearson’s correlation coefficient. Multiple linear regression analysis, with forced entry of the psychological measures in addition to a schizotypy measure, was used in the prediction of RMS. This analysis was performed to account for the
impact of the control variables on the associations between the schizotypy indices and RMS. We also examined time durations and underestimation of self-movements relating to prediction error.

3. Results

One participant was excluded due to excessive mouse movement. He apparently did not understand the experimental procedure. The means and standard deviations for each of the measures assessed in this study are shown in Table 1. Table 1 also contains information on the handedness, psychological measures (i.e., anxiety, depression), schizotypal personality traits, and experimental performances for the participants. Table 1 also includes normative data from questionnaires conducted in Japan and the UK; the former are based on our preliminary surveys and the latter are based on two previous studies (Annett & Moran, 2006; Mason et al., 1995). The sample mean scores are broadly comparable with the normative means, although they are somewhat larger than the mean scores from Japan.

The intercorrelations of the questionnaire indices are shown in Table 2. Focusing on positive schizotypal personality traits (i.e., STA, AHES, and UnEx in O-LIFE), STA had significant correlations with STAI, AHES, and O-LIFE (UnEx and CoDi); AHES had significant correlations with STA and O-LIFE (UnEx); and UnEx had significant correlations with STA, AHES, and O-LIFE (CoDi). Although these indices, as one would expect, have correlations with each other, AHES had the highest discrimination of positive schizotypal personality traits. AHES had no correlation with STAI or CoDi.

The intercorrelations of the movement prediction error (RMS) are contained in Table 3. Table 3 presents information on RMS movement prediction error for each hand and each quadrant of the participants. Total right-hand RMS (collapsed across quadrants) was significantly correlated with total left-hand RMS, and total RMSs (for the right or left hand) were significantly correlated with the RMSs of each of the four quadrants. Thus, participants performed similarly, regardless of quadrant or hand. The high correlations between the total RMSs and RMSs for each of the four quadrants meant that we did not have to be concerned with the quadrant; thus, we used the total RMSs (right or left hand) regardless of quadrant in the following analysis.

3.1. Relationship between positive schizotypy and movement prediction error

Using RMS as the dependent measure, we examined the associations between questionnaire indices, especially positive schizotypy (i.e., STA, AHES, and UnEx in O-LIFE) and RMS; these correlations can be found in Table 4. Whereas right-handed RMS did not correlate with any scale, left-handed RMS was significantly correlated with STA, AHES, and CoDi in O-LIFE. For example, Fig. 3 shows the relationship between left-handed RMS and AHES, which had the strongest correlation, and illustrates that high-AHES individuals clicked the farthest from the targets in all quadrants. One-way analysis of variance (ANOVA) indicated a significant main effect of AHES group ($F(2, 39) = 3.50, P < .05$). Multiple comparison using Tukey’s HSD indicated a significant difference between low- and high-AHES groups ($P < .05$).

Table 1

<table>
<thead>
<tr>
<th>Measure</th>
<th>Sample Mean (SD)</th>
<th>Norms1 (JP) Mean (SD)</th>
<th>Norms2 (UK) Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Handedness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annett Handedness Scale</td>
<td>1.9 (1.2)</td>
<td>2.1 (1.5)</td>
<td>2.3 (NA)*</td>
</tr>
<tr>
<td><strong>Psychological measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beck Depression Inventory</td>
<td>10.6 (6.8)</td>
<td>10.5 (6.7)</td>
<td></td>
</tr>
<tr>
<td>Spielberger-Trait Anxiety</td>
<td>48.9 (9.6)</td>
<td>48.7 (10.2)</td>
<td></td>
</tr>
<tr>
<td><strong>Schizotypal personality traits</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxford Schizotypal Personality Scale</td>
<td>12.1 (6.0)</td>
<td>11.2 (6.2)</td>
<td>15.9 (NA)*</td>
</tr>
<tr>
<td>Auditory Hallucination Experience Scale</td>
<td>60.1 (21.4)</td>
<td>59.6 (24.9)</td>
<td></td>
</tr>
<tr>
<td>Oxford-Liverpool Inventory of Feelings and Experiences</td>
<td>37.2 (11.5)</td>
<td>37.5 (11.7)</td>
<td>40.1 (NA)*</td>
</tr>
<tr>
<td>Unusual Experiences</td>
<td>5.9 (4.5)</td>
<td>6.1 (4.3)</td>
<td>11.6 (6.8)*</td>
</tr>
<tr>
<td>Introvertive Anhedonia</td>
<td>8.8 (5.0)</td>
<td>8.5 (5.3)</td>
<td>5.1 (4.2)*</td>
</tr>
<tr>
<td>Cognitive Disorganization</td>
<td>14.2 (5.0)</td>
<td>13.3 (5.3)</td>
<td>12.6 (5.3)*</td>
</tr>
<tr>
<td>Impulsive Non-conformity</td>
<td>8.4 (3.3)</td>
<td>9.6 (3.4)</td>
<td>10.8 (4.1)*</td>
</tr>
<tr>
<td><strong>Experimental performance</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Movement prediction error (root-mean-square)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right hand</td>
<td>88.4 (27.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left hand</td>
<td>87.5 (31.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement time duration</td>
<td>2532 (841.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right hand</td>
<td>2549 (845.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underestimation of self-movement</td>
<td>8.5 (24.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right hand</td>
<td>19.9 (34.1)</td>
<td></td>
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</tr>
</tbody>
</table>

Note: Norms1 is based on our preliminary surveys of a large sample from Japan; Norms2 is based on data from the UK from Annett and Moran (2006)* and Mason et al. (1995)*.
We examined whether positive schizotypy measures (AHES, STA, and UnEx in O-LIFE) can predict left-handed RMS using multiple linear regression analysis. We used a simultaneous regression procedure with forced entry of the psychological measures (anxiety, depression), handedness, gender, and age, as well as a schizotypy measure in the prediction of left-handed RMS. This analysis was conducted to take into account the impact of the control variables on the associations between the schizotypy indices and left-handed RMS. A separate regression was conducted for each of the three positive schizotypy indices in the prediction of left-handed RMS; the results of these analyses are shown in Table 5.

As shown in Table 5, even with the forced entry of measures of depression, trait anxiety, handedness, age, and gender along with a schizotypy index, both the STA and AHES scales made significant contributions to the explanation of left-handed RMS, as the previous correlation analysis suggested. These data clearly suggest that depression and anxiety do not explain the relationship observed between schizotypy and the left-handed RMS.

### Table 2
**Intercorrelations of the questionnaire measures**

<table>
<thead>
<tr>
<th>Index</th>
<th>AHPQ</th>
<th>BDI</th>
<th>STAI</th>
<th>STA</th>
<th>AHES</th>
<th>O-LIFE</th>
<th>UnEx</th>
<th>InAn</th>
<th>CoDi</th>
<th>ImNo</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHPQ</td>
<td></td>
<td>.02</td>
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<td>.08</td>
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<td>.29</td>
<td>.00</td>
<td>.22</td>
<td>.20</td>
<td>.00</td>
</tr>
<tr>
<td>BDI</td>
<td>.02</td>
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<td>.57</td>
<td></td>
<td>.43</td>
<td>.57</td>
<td>.61</td>
<td>.08</td>
<td>.49</td>
<td>.46</td>
</tr>
<tr>
<td>STAI</td>
<td>.08</td>
<td>.57</td>
<td></td>
<td>.24</td>
<td>.23</td>
<td>.12</td>
<td>.12</td>
<td>.08</td>
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<td>.16</td>
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<td>STA</td>
<td>.24</td>
<td>.23</td>
<td>.43</td>
<td></td>
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<td>.58</td>
<td>.57</td>
<td>.20</td>
<td>.52</td>
<td>.18</td>
</tr>
<tr>
<td>AHES</td>
<td>.29</td>
<td>.12</td>
<td>.06</td>
<td>.58</td>
<td></td>
<td>.71</td>
<td>.39</td>
<td>.55</td>
<td>.31</td>
<td>.29</td>
</tr>
<tr>
<td>O-LIFE</td>
<td>.00</td>
<td>.12</td>
<td>.06</td>
<td>.58</td>
<td>.71</td>
<td></td>
<td>.63</td>
<td>.55</td>
<td>.83</td>
<td>.52</td>
</tr>
<tr>
<td>UnEx</td>
<td>.22</td>
<td>.08</td>
<td>.20</td>
<td>.56</td>
<td>.39</td>
<td>.63</td>
<td></td>
<td>.17</td>
<td>.31</td>
<td>.08</td>
</tr>
<tr>
<td>InAn</td>
<td>.00</td>
<td>.08</td>
<td>.20</td>
<td>.52</td>
<td>.40</td>
<td>.08</td>
<td>.17</td>
<td></td>
<td>.26</td>
<td>.13</td>
</tr>
<tr>
<td>CoDi</td>
<td>.20</td>
<td>.49</td>
<td>.51</td>
<td>.58</td>
<td>.31</td>
<td>.83</td>
<td>.31</td>
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<td>.57</td>
</tr>
<tr>
<td>ImNo</td>
<td>.00</td>
<td>.46</td>
<td>.16</td>
<td>.18</td>
<td>.29</td>
<td>.52</td>
<td>.08</td>
<td>.13</td>
<td>.57</td>
<td></td>
</tr>
</tbody>
</table>

Note: N = 40. Values are Pearson correlation coefficients. Correlations were tested for statistical significance using a two-tailed procedure. AHPQ = Annett Handedness Preference Questionnaire, BDI = Beck Depression Inventory, STAI = State-Trait Anxiety Inventory, STA = Oxford Schizotypal Personality Scale, AHES = Auditory Hallucination Experience Scale, O-LIFE = Oxford-Liverpool Inventory of Feelings and Experiences, UnEx = Unusual Experiences, InAn = Introvertive Anhedonia, CoDi = Cognitive Disorganization, ImNo = Impulsive Non-conformity.

* p < 0.05.
** p < 0.01.

### Table 3
**Intercorrelations of the RMS with both hands and four quadrants**

<table>
<thead>
<tr>
<th>Right-hand RMS</th>
<th>Left-hand RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Right-hand RMS</strong></td>
<td></td>
</tr>
<tr>
<td>First quadrant</td>
<td>.79**</td>
</tr>
<tr>
<td>Second quadrant</td>
<td>.68**</td>
</tr>
<tr>
<td>Third quadrant</td>
<td>.63**</td>
</tr>
<tr>
<td>Fourth quadrant</td>
<td>.81**</td>
</tr>
<tr>
<td><strong>Left-hand RMS</strong></td>
<td>.64**</td>
</tr>
<tr>
<td>First quadrant</td>
<td>.69**</td>
</tr>
<tr>
<td>Second quadrant</td>
<td>.44**</td>
</tr>
<tr>
<td>Third quadrant</td>
<td>.31**</td>
</tr>
<tr>
<td>Fourth quadrant</td>
<td>.61**</td>
</tr>
</tbody>
</table>

Note: N = 40. Values are Pearson correlation coefficients. Correlations were tested for statistical significance using a one-tailed procedure based on an a priori directional hypothesis. RMS = root mean square of one’s own movement prediction error. Right (Left)-hand RMS = total right (left)-hand RMS collapsed across quadrants.

* p < 0.05.
** p < 0.01.

### Table 4
**Intercorrelations of questionnaires and movement prediction errors**

<table>
<thead>
<tr>
<th>AHPQ</th>
<th>BDI</th>
<th>STAI</th>
<th>STA</th>
<th>AHES</th>
<th>O-LIFE</th>
<th>UnEx</th>
<th>InAn</th>
<th>CoDi</th>
<th>ImNo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right-hand RMS</td>
<td>-.03</td>
<td>.06</td>
<td>.14</td>
<td>.08</td>
<td>.15</td>
<td>.04</td>
<td>.11</td>
<td>-.14</td>
<td>.02</td>
</tr>
<tr>
<td>Left-hand RMS</td>
<td>-.22</td>
<td>.06</td>
<td>.15</td>
<td>.27**</td>
<td>.41**</td>
<td>.14</td>
<td>.08</td>
<td>-.17</td>
<td>.32**</td>
</tr>
</tbody>
</table>

Note: N = 40. Values are Pearson correlation coefficients. Correlations were tested for statistical significance using a one-tailed procedure based on an a priori directional hypothesis. RMS = root mean square of one’s own movement prediction error. AHPQ = Annett Handedness Preference Questionnaire, BDI = Beck Depression Inventory, STAI = State-Trait Anxiety Inventory, STA = Oxford Schizotypal Personality Scale, AHES = Auditory Hallucination Experience Scale, O-LIFE = Oxford-Liverpool Inventory of Feelings and Experiences, UnEx = Unusual Experiences, InAn = Introvertive Anhedonia, CoDi = Cognitive Disorganization, ImNo = Impulsive Non-conformity.

* p < 0.05.
** p < 0.01.
3.2. Relationship between positive schizotypy and time duration of the movements

We established a relationship between positive schizotypy, especially proneness to auditory hallucinations, and a participant’s own movement prediction error using the left hand. The correlation of high AHES (Auditory Hallucination Experience Scale) with the highest error rate could have been an artifact, in that those participants may have performed the experimental task less carefully or seriously or may have been less adept with mouse devices. To eliminate these artifacts, we examined the time duration of participant movements. First, we examined the relationship between time duration and prediction error in each hand. Could participants who took more time have been more accurate? However, correlation analysis showed no association between time duration and prediction error. Second, we examined the relationship between time duration and questionnaire measures, but again correlation analysis revealed no relationship. These results suggest that artifacts were not factors in the correlation.

3.3. Relationship between positive schizotypy and underestimation of self-movements

We investigated the possible relationship of prediction error patterns to positive schizotypy. We hypothesized that positive schizotypy, including auditory hallucination-like experiences, is related to participants’ underestimation of their movements. Table 6 shows correlations of the relationship between questionnaire measures and underestimation of self-movement values. Whereas the only significant correlation of right-handed performances was to ImNo in O-LIFE, left-handed performances were significantly correlated with BDI, AHES, O-LIFE, and CoDi in O-LIFE. Of these, correlations between underestimating left handed movements and AHES and CoDi in O-LIFE are in accord with similar relationships to prediction error. We also used a simultaneous regression procedure in analyzing the underestimation of self-movements but did not obtain any significant results.

4. Discussion

The present study produced some interesting results. However, because of the small number of participants, we must regard the findings as preliminary. We mainly examined the relationship between the prediction of one’s own movements and schizotypal personality traits, especially positive schizotypy. Passivity phenomena of schizophrenic positive symptoms, including auditory hallucinations, may be caused by abnormal predictions of one’s own movements or actions (Blakemore et al., 2002; Frith et al., 2000a, 2000b).

Both the correlation and regression analyses revealed that the prediction error of left-hand movements was related to schizotypal personality traits, and not to depressive or anxiety proneness. This result does not reflect the general motor control performance or strategy of participants, which is reflected in the time duration of their movements. Movement time is a measure of movement execution that is separate from motor prediction or planning. People with schizophrenia have been found to demonstrate abnormal movement planning, despite having normal movement execution (Carnahan et al., 1997). Of
the schizotypal personality traits, positive schizotypy (STA), auditory hallucination proneness (AHES), and cognitive disorganization (CoDi) were significantly correlated with the prediction error (RMS) of their left hand as measured by the experiments. Because positive schizotypy includes passivity phenomena and passivity phenomena include auditory hallucinations, the correlation with STA or AHES is a reasonable result. Researchers continue to debate cognitive disorganization in schizophrenia or schizotypy. Although a three-factor theory that includes cognitive disorganization has been suggested (Bentall, Claridge, & Slade, 1989), a classical and still powerful classification of schizophrenic symptoms derived from Crow (1980) is the two-factor theory of positive and negative symptoms. Cognitive disorganization mainly refers to cognitive and attention disorders. This factor may be closely related to positive symptoms or passivity phenomena. Indeed, Asai and Tanno (2007b) reported that the positive and cognitive disorganization factors of schizotypy cause difficulty in integrating visual and auditory information, which may lead to positive symptoms. Although unusual experiences (UnEx) also indicate positive experiences.

We need to consider why only the left-handed RMS is related to the schizotypal personality. Although, we did not have enough left-handed participants for a statistical comparison, left handers seemed to perform as well as right handers. One possibility is that because the participants usually manipulate the mouse with their right hand (all participants, including left handers, said that they use the mouse device with their right hand), differences in their difficulty in predicting their hand movements may decrease. Indeed, the correlation between right and left was strong (r = .64, prediction error; r = .85, time duration). That is, participants performed equally with their right and left hands; i.e., someone who performed badly with the right hand also performed badly with the left hand. However, individual right-handed RMS differences might be diminished because of daily right-handed use of the mouse device. Indeed, the SD for right-handed RMS was less than that for left-handed RMS (see Table 1). More speculatively, the results might be related to potential laterality regarding the prediction of
The abnormal forward output model has also increased. (Feinberg & Guazzelli, 1999; Ford & Mathalon, 2004, 2005; Ford et al., 2007). The less the subject felt in control of the movements of the virtual hand, the higher the activation level in the right inferior parietal lobe (Farrer et al., 2003). This brain area was activated in schizophrenia patients while under a declined feeling of control (Spence et al., 1997), or even during rest (Franck, O'Leary, Flaum, Hichwa, & Andreasen, 2002). The possible relation of these brain areas to a weaker sense of agency might explain why individual differences in the extent of schizotypal traits could be detected in the participants' left-hand performances, which are controlled by the motor area in the same hemisphere. From another perspective, the controller of the preferred hand might be more adapted for closed-loop movement control (feedback control), whereas the controller of the non-preferred hand seems to be better prepared for open-loop movement control (feed-forward control; Lenhard & Hoffmann, 2007). The left hand, which might have to access the internal model to create feed-forward control (Heue & Hegele, 2008), might reflect the abnormal internal model more than does the right hand, especially for the forward dynamic model examined here.

Passivity phenomena, including auditory hallucinations, may be caused by abnormal predictions of one's own movements or actions (Blakemore et al., 2002; Frith et al., 2000a, 2000b). The result, that the auditory hallucination proneness had the strongest association with the one's own prediction error, corresponds to claims at the level of schizotypal personality. For example, it has been reported that people with schizophrenic positive symptoms or passivity phenomena have deficits in the rapid correction of their arm movements (Frith & Done, 1988) and have poor motor control (Blyler, Maher, Manschreck, & Fenton, 1997), dysfunctions in motor imagery (Maruff, Wilson, & Currie, 2003), and deficits in predicting their body positions (Fournier et al., 2002). In addition, Lenzenweger and Maher (2002) showed that subjects with positive schizotypy exhibit abnormal motor control. Although these studies suggested that positive symptoms, especially passivity phenomena, may be related to the abnormal prediction of one's own movements or actions, the present study showed that relationship in a more direct way using no visual feedback motor control task (Ogawa & Inui, 2007; Ogawa et al., 2006), in which they had to predict their own movement without visual feedbacks.

Moreover, an advantage of the paradigm used in the present study enables us to examine the tendency of the prediction error in terms of the overestimation or underestimation of one's own movements. We demonstrated an association between auditory hallucination proneness and underestimation of self-movements. Given that the underestimation value is highly affected by the prediction error value ($r = .65$ in the left hand), the correlation with BDI, for example, means that participants with high BDI predicted their movements as well as those with low BDI but tended to overshoot targets more often. Conversely, the underestimation value becomes larger for participants with large prediction errors but indicates an equal tendency to overshoot compared to other participants. The tendency only to overshoot may not be critical if the extent of the error is not severe. However, the relationship of auditory hallucination proneness to both large prediction error and underestimation of self-movements is important. Unfortunately, we were unable to demonstrate a strong statistical relationship between auditory hallucination proneness and underestimation of self-movements. Because we were mainly interested in investigating the extent of participant prediction error in this experiment, we placed the targets in difficult pointing positions that required participants to move on the angle in order to reveal individual differences. In a study focusing on the underestimation of self-movements, vertical or horizontal movements, such as those in the Lenhard and Hoffmann (2007) paradigm may be suitable, as participants rarely moved on the angle incorrectly. In the case of auditory hallucinations, one's own speech may be an important factor (McGuigan, 1966) in that they may be caused by underestimating speech. In the same way, it is possible that auditory hallucination proneness is related to underestimating one's movements. Moreover, the weaker sense of agency displayed by people with highly positive schizotypy (Asai & Tanno, 2007a, 2008) may be coincident with the underestimation of self-movements. For example, since the bodies of schizotypic people move more than they expect, they may not feel that it is their own movement. As the experimental paradigm improves, further research will be able to examine this question. Another limitation of our experiment was that participants' hand movements did not match their visual feedback (i.e., they had only terminal visual feedback, not continuous feedback) in space location (see Fig. 2). Although the present paradigm was similar to that used in previous studies, it might be better to match the spatial locations to avoid potential noise (i.e., such as in a non-PC-based experiment like that by Lenzenweger & Maher, 2002), including individual differences in visual distance estimation. By so doing, we expect that our weak, but statistically significant, correlations would become stronger.

As for the association with the computational model of motor control (Miall & Wolpert, 1996; Wolpert, 1997), our study shows that schizotypal personality traits are associated with the abnormal dynamic forward model, which can lead to an abnormal sense of agency in positive schizotypy (Asai & Tanno, 2007a, 2008) and in schizophrenic patients exhibiting passivity phenomena (Daprati et al., 1997; Franck et al., 2001) because the abnormal dynamic model would predict abnormal movement in people with schizotypal traits, as was found here. The evidence, however, that schizophrenic patients exhibit the abnormal forward output model has also increased. (Feinberg & Guazzelli, 1999; Ford & Mathalon, 2004, 2005; Ford et al., 2001; Shergill et al., 2005). No study has yet suggested that schizotypy is associated with the abnormal forward output model, but additional studies may be able to establish this link. In addition, people with (positive) schizophrenia or schizotypy may exhibit the abnormal information comparator (Asai & Tanno, 2007b; de Gelder, Vroomen, Annen, Masthoff, & Hodiamont, 2002; de Gelder et al., 2005; Peled, Pressman, Geva, & Modai, 2003; Peled, Kitsner, Hirschmann, Geva, & Modai, 2000). Although the neural correlations for each component of forward modeling are still unclear, the dynamic forward model, dynamic output model, and comparator might be related to the PPC (Ogawa & Inui, 2007; Ogawa, Inui, & Sugio, 2007).
cerebellum (Blakemore, Wolpert, & Frith, 1998, 1999, 2001), and EBA (David et al., 2007), respectively. Whenever the abnormalities that cause an abnormal sense of agency (Frith, 2005), this sense might be derived from the abnormal forward dynamic model or the abnormal production of an effference copy in the sense that the forward output model and comparator receive the information from the forward dynamic model. Patients experiencing passivity phenomena may have particular impairments of parietal function related to the poor use of forward models of intended actions (Danckert et al., 2004). Further research is required to verify the abnormal forward dynamic model or PPC.

References


Feinberg, I., & Guazzelli, M. (1999). Schizophrenia – A disorder of the corollary discharge systems that integrate the motor systems of thought with the sensory systems of consciousness. The Royal College of Psychiatrists, 174, 196–204.


