Original Article

Psychotic Symptoms Predicting Evidence Integration in Schizophrenia

A Multivariate Analysis of the BADE Task

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Abstract: A bias against disconfirmatory evidence (BADE) is a cognitive bias associated with delusions in schizophrenia. Previous studies reporting an association between reduced evidence integration and delusions used a single measure of delusion severity, typically to form patient groups. In the current study we perform an exploratory analysis to investigate whether BADE is specific to delusions or extends to other symptoms of psychosis. To address this, we used constrained principal component analysis (CPCA) on four merged BADE studies on schizophrenia to explore the component structure in the BADE task measures that is predictable from symptoms. A component reflecting evidence integration emerged, and was predicted by delusions as expected, but also by thought disorder. This provides novel methodology for cognitive neuropsychiatric investigations into the underpinnings of the symptoms of schizophrenia by enabling investigators to consider a range of symptoms alongside the one that is the target of their investigation.

Keywords: bias against disconfirmatory evidence (BADE), decision making, delusions, thought disorder, constrained principal component analysis

Delusions, defined as fixed false beliefs held with great conviction in the face of counter-evidence (American Psychiatric Association, 2000), are a hallmark symptom of schizophrenia. A bias against disconfirmatory evidence (BADE) is a measurable cognitive bias that has been shown to be associated with delusions in schizophrenia. BADE is the tendency to maintain an initially held interpretation despite being provided with disconfirmatory evidence. This cognitive bias has been found to be particularly associated with delusions or delusional ideation in psychiatric and healthy populations (Buchy, Woodward, & Liotti, 2007; Sanford, Veckenstedt, Moritz, Balzan, & Woodward, 2014; Woodward, Buchy, Moritz, & Liotti, 2007; Woodward, Moritz, & Chen, 2006; Woodward, Moritz, Menon, & Klinge, 2008). Although BADE tasks have been developed in various forms, they all require participants to change their initial ratings of a few competing scenario interpretations when provided with an increasingly clarifying context (Sanford et al., 2014; Speechley, Ngan, Moritz, & Woodward, 2012; Woodward, Moritz, Cuttler, & Whitman, 2006; Woodward et al., 2007).

Two empirically derived dominant cognitive operations involved in the BADE task have been previously identified as "evidence integration," which describes the ability to incorporate disconfirming information into an interpretation of a scenario, and "response conservatism," which reflects a tendency in some individuals to rate low on initial ratings regardless of interpretation plausibility (Sanford et al., 2014; Speechley et al., 2012). Successful evidence integration involves simultaneous down rating of an initially plausible interpretation (change from high to low rating) and uprating of an initially implausible interpretation (change from low to high) as the scenario becomes increasingly disambiguated with successive presentation of evidence, and also consistent low ratings for absurd interpretations. Evidence integration has been demonstrated to be weakened when delusion severity is high, whereas response conservatism has not been related to delusion severity (Sanford et al., 2014; Speechley et al., 2012). Typically, association with delusion severity has been based on group comparisons, with the groups determined using a single measure of delusions. Therefore, it has never

been thoroughly explored whether the BADE effect is specific to delusions, or if it extends to other symptoms of psychosis, this being goal of the current study.

In previous studies (Sanford et al., 2014; Speechley et al., 2012), computation of evidence integration and response conservatism were derived from a principal component analysis (PCA) on the 12 BADE measures (i.e., 4 interpretations rated 3 times), with only the evidence integration component scores showing differences between delusional and non-delusional groups of schizophrenia patients. These PCA-derived components index the primary dimensions of the BADE task, but they are not optimized to reflect the variance in the BADE measures that are *specifically predictable from symptoms*. This is an important distinction to make, as the latter may substantially differ from the former. In order to determine the primary dimensions of BADE scores that are optimally predicted from symptoms, we must *first* carry out multiple regression to isolate the BADE variance predictable from symptoms, *then* carry out PCA on the symptom-variance-constrained BADE scores. That sequence of analysis steps is a special case of a more general method referred to as constrained principal component analysis (CPCA; Hunter & Takane, 1998, 2002; Takane & Hunter, 2001; Takane & Shibayama, 1991) which combines multivariate multiple regression and PCA. In this application, the multivariate multiple regression step isolates symptom-related variance in BADE scores, allowing computation of the symptom-relevant BADE components by carrying out PCA on the variance constrained that predictable from symptoms.

In the present study, we simultaneously analyze four BADE datasets which all included symptom assessment using and the Signs and Symptoms of Psychotic Illness (SSPI) rating scale (Liddle, Ngan, Duffield, Kho, & Warren, 2002). CPCA was used to isolate symptom-related variance in BADE scores, optimizing computation of the BADE components using PCA constrained to variance predictable from symptoms, allowing for exploration of the BADE measures predictable from a range of psychotic symptoms in a large sample size.

Method

Participants

Data were derived from four studies that administered the BADE task and recorded SSPI symptoms in schizophrenia. In total, data from 179 participants with a diagnosis of schizophrenia or schizoaffective disorder were analyzed. Demographic information about each study sample is presented in Table 1. For all samples, participants were excluded if they had a history of *DSM*-defined substance abuse, or if they had experienced a head injury that resulted in a loss of consciousness for greater than 10 min. All diagnoses were based on *DSM-IV-R* criteria (American Psychiatric Association, 2000) and were taken from a chart review. These diagnoses were based on a multidisciplinary team conference during the first month of admission when the diagnosis is reviewed using all sources of information. If a diagnosis had not been finalized at the time of recruitment, the Mini-International Neuropsychiatric Interview (MINI; Sheehan et al., 1998) was administered on the date of testing to provide a final diagnosis.

In order to ensure homogeneity across samples, between-group analyses of demographic information were carried out (e.g., age, sex, length of illness), and structural equation modeling using generalized structured component analysis (GSCA; Hwang & Takane, 2004) was used to ensure that the factor structure was equivalent between samples.

Table 1. Demographic details of participants and BADE task details of different studies used

Study	Number of participants	Gender ratio (males:females)	Mean age in years (*SD*)	BADE task stimuli	Number of scenarios	Number of interpretations
Woodward, Moritz, Cuttler, et al. (2006). The contribution of a cognitive bias against disconfirmatory evidence (BADE) to delusions in schizophrenia.	52	39:13	38.07 (9.50)	Pictures	10	4
Speechley et al. (2012). Impaired Evidence Integration and Delusions in Schizophrenia.	50	35:15	38.23 (11.99)	Sentences	30	4
Unpublished (2006).	28	17:11	28.68 (7.29)	Sentences	25	3 (1 lure)
Unpublished (2011).	49	29:20	34.88 (9.84)	Sentences	12	4

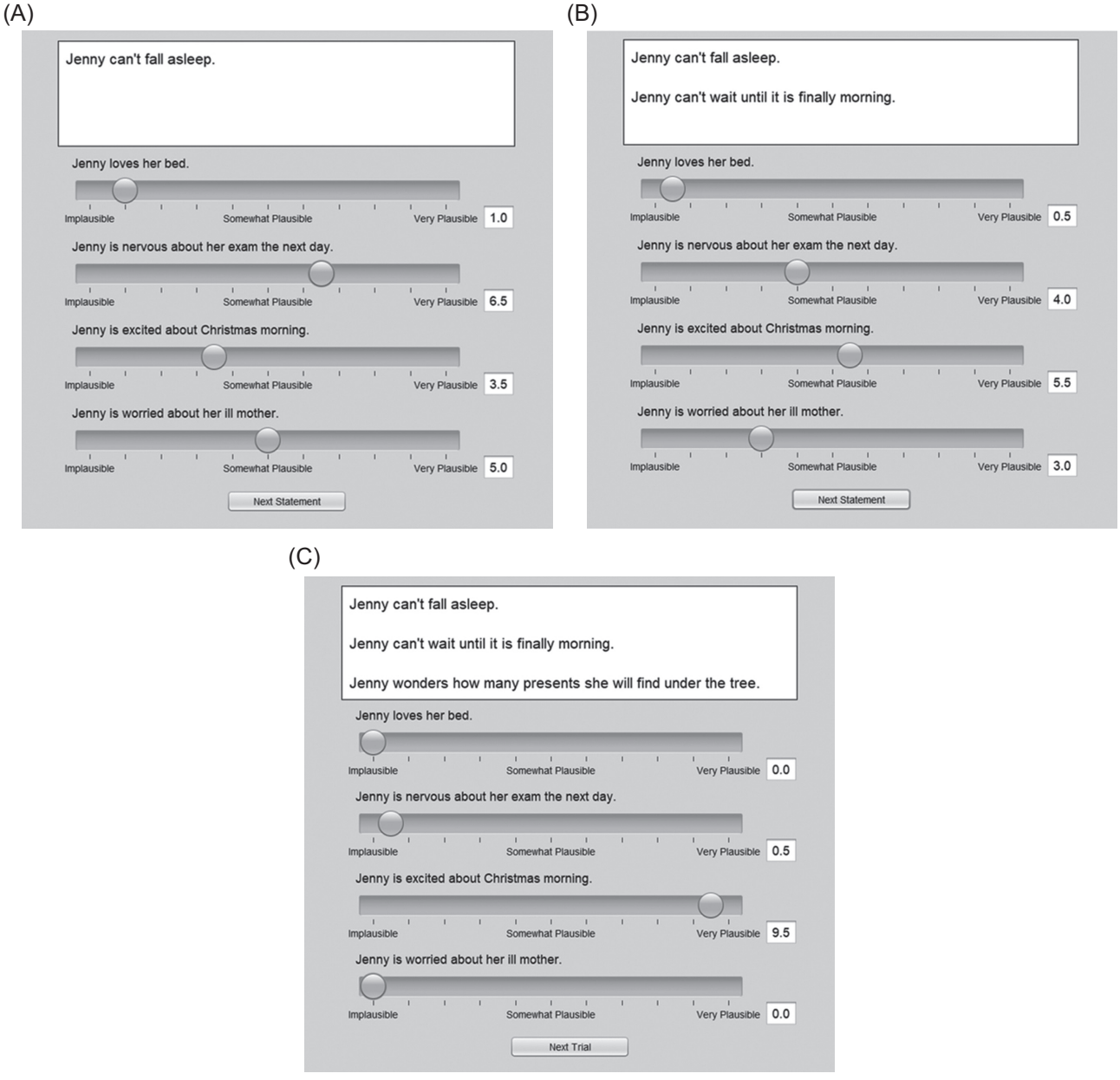

Figure 1. Typical bias against disconfirmatory evidence (BADE) trial, whereby three disambiguating screen displays are presented in sequence. (A) Participants are first presented with a scenario described with limited information and asked to rate each of the possible interpretations on a scale of 1–10, with 1 being least likely and 10 being most likely. (B) The second screen adds another sentence, which provides more information to disambiguate the scenario, and participants are given the opportunity to re-rate all four interpretations. (C) The final sentence is presented, providing all necessary information to interpret the scenario. Participants are given the opportunity to re-rate all possible interpretations a third and final time. (The labels A, B, and C were not displayed in the BADE task but are displayed here to clarify screen display order).

BADE Task

The four previously collected datasets all used different versions of the BADE task (see Table 1 for details). All versions of the BADE task involve presentation of scenarios that are accompanied by three (or four) possible interpretations, individually rated and re-rated after each of three successively presented statements (illustrated in Figure 1): one absurd interpretation, which seems implausible from the first statement and remains so throughout the trial; one (or two) lure interpretations, which seems plausible initially but is disconfirmed after the second or third statement; and one true interpretation, which does not seem to be the most plausible from the start, but is confirmed to be true by the final statement. For example, the statement "Jenny can't fall asleep" may be interpreted several ways (e.g., "Jenny

is worried about her exam the next day" or "Jenny is excited about Christmas morning"); as more statements are presented (e.g., "Jenny can't wait until it's finally morning"), it becomes increasingly clear as to which interpretations are lures, which are true, and which are absurd. Participants are asked to rate the plausibility of each of the three (or four) possible interpretations, and are given the opportunity to re-rate each interpretation with the presentation of each new piece of evidence. For one of the four datasets (i.e., Table 1 unpublished dataset 2006), participants were presented with three possible interpretations only, with one "True," one "Lure," and one "Absurd" interpretation. The remainder of the studies have an additional "Lure" in addition to the previously described three interpretations, to total four possible interpretations. The scenarios are presented to the participant through pictures (Woodward, Moritz, Cuttler, et al., 2006) or sentences (e.g., Speechley et al., 2012), and all interpretations are presented in sentence form. Thus, a BADE trial is a full presentation of a scenario, all interpretations and all disambiguating information, from start to finish, which always involves an initial rating of interpretations, and two rating adjustment opportunities.

Signs and Symptoms of Psychotic Illness (SSPI) Rating Scale

The SSPI (Liddle et al., 2002) was used to measure symptoms. The SSPI is a 20-item, 5-point rating scale, which can be completed after a 25–30 min semi-structured interview with 15 direct questions about symptoms. The severity of each item is rated in the range of 0–4. The SSPI provides specific guidelines for the severity level of each item, but generally, a score of 1 = *questionable abnormality*, 2 = *definite severe psychopathology*. The SSPI is administered in a structured interview format based on the Present State Examination (Wing, Birley, Graham, & Isaacs, 1967). Participants all underwent the SSPI interview and assessment for the full range of symptoms; however, for this analysis, we particularly chose to analyze a subset of seven symptoms, because these are the core symptoms of the three syndrome model, based on previous analysis of the SSPI (Liddle, 1987; Woodward, Ruff, Thornton, Moritz, & Liddle, 2003; Woodward et al., 2004). These were the presence and/or severity of delusions (M = 2.11, SD = 1.46), hallucinations (M = 1.34, SD = 1.70), underactivity of motor behavior (M = 0.68, SD = 0.92), flattened affect (M = 0.96, SD = 1.06), inappropriate affect (M = 0.30, SD = 0.78), poverty of speech (M = 0.39, SD = 0.85), and thought disorder (M = 0.77, SD = 1.06). Therefore, the SSPI items not included in the analysis were anxiety, depression, anhedonia, elated mood, insomnia, somatic complaints, attentional impairment, disorientation, overactivity of motor activity, pressure of speech, peculiar behavior, irritability/hostility, and impaired insight of nature of illness.

Constrained Principal Component Analysis

To delineate the relationship between the BADE task and symptomology, this study utilized CPCA, a technique that combines multivariate multiple regression with PCA to reveal orthogonal sources of variation within the data. Details of the theory and proofs for this technique can be found elsewhere (Hunter & Takane, 1998, 2002; Takane & Hunter, 2001; Takane & Shibayama, 1991). Briefly, CPCA can be divided into two main steps, the external and internal analyses. The external analysis involves a multivariate multiple regression to separate the total variance in the dependent variable (Z) into that which is predictable from the predictor variables (G) and variance that is not. This produces two matrices: one composed of variance predictable by the predictor variables, or regression-based predicted scores (GC), and the residual or error scores (E). The external analysis can be denoted by the regression equation:

$$Z = GC + E,$$

where $C = (G'G)^{-1}G'Z$ is a matrix of regression coefficients which when applied to G produced a matrix of predicted scores (GC). Z = matrix of dependent variables and E = residual scores (variance in Z not explained by predictor variables in G).

The internal analysis in this case involves submitting the predicted scores (GC) to a PCA. Component scores resulting from the PCA on GC are then correlated with the columns of G to create predictor loadings. Predictor loadings indicate the degree to which each independent variable (SSPI items for this analysis) is related to each component score extracted in the PCA of GC (recall that GC contains the BADE item variance that is predictable from SSPI symptoms). In the current study, mean ratings for the true, absurd, and lure interpretations were computed for each participant averaged over all scenarios (the number of scenarios for each BADE test are listed in Table 1, column 6). In the finalized merged dataset, the two lures in the three datasets that presented four interpretations were averaged to equate the number of BADE variables in all four data sets (one fewer lure was present in the unpublished 2006 study, see Table 1). The resulting 9 BADE items (i.e., true 1, true 2, true 3, absurd 1, absurd 2, absurd 3, lure 1, lure 2, lure 3) comprised the Z matrix (179 participants × 9 BADE item ratings). The G matrix (i.e., the predictor variables) consisted of SSPI items 7, 8, 12, 13, 14, 16, and 17 (delusions, hallucinations, underactivity of motor behavior, flattened affect, inappropriate affect, poverty of speech, thought

disorder, respectively; 179 participants × 7 SSPI items). Visual inspection of scree plots (Cattell, 1966; Cattell & Vogelmann, 1977) resulting for the PCA on both *Z* and *GC* determined the number of components to be extracted for each solution. Varimax rotation with Kaiser normalization was applied. All computations were performed using MATLAB R2016b software.

Permutation Test for Significance

A permutation test was carried out to test the statistical significance of the variance predicted by symptoms (Takane & Hwang, 2002). Specifically, the BADE item ratings matrix (*Z* matrix) was randomly permuted by rows and tested for variance predictable from SSPI symptoms. Here, we tested 10,000 permutations of the *Z* matrix. If the percent of variance on the BADE ratings is significantly predictable from symptoms, then fewer than 5% of the permuted variances will be higher than the original percentage of predictable variance in the (not permuted) dataset.

Results

Analysis of demographic differences between the four participant subsamples yielded no significant differences between subsamples. The Fit statistics (which define the variance accounted for by each model) for two GSCA models were compared using the evidence integration and response conservatism factor structures, one model allowing the factor structure to be freely estimated for each subsample separately, and the other forcing the factor structure to be the same in all four subsamples (see Woodward et al., 2014 for similar methodology). Bootstrapping (n = 100) confirmed no significant difference between these models, justifying combining of the four subsamples into one large sample with one factor structure.

Table 2 shows the distribution of variance in BADE scores, for both the internal and external analyses. The external analysis revealed that SSPI symptoms accounted for 6.20% of variance in the BADE scores ($p < .05$), which is considered a medium-to-small effect, with a medium effect size being 9% variance accounted for (Pearson's r = 0.30, Cohen's d = 0.50) and a small effect size being 1% (Pearson's r = 0.10, Cohen's d = 0.20). The internal analysis shows the results of the PCA on the *Z* and *GC* solutions and indicates the numerical and percentage variance accounted for by the components of each.

Table 3 lists the component loadings for the *Z* (overall) analysis. This is a standard PCA that does not distinguish between variation predictable and not predictable from SSPI symptoms. In line with results from previous studies (Sanford et al., 2014; Speechley et al., 2010; Woodward et al., 2007), two components emerged and were interpreted as evidence integration and response conservatism. Table 4 shows the structure of the SSPI predictable solution *GC*, where evidence integration emerged as Component 1,

Table 2. Constrained principal component analysis variance table

	External analysis	Internal analysis (PCA) 1	2	Total
Total	9.0	3.9	3.2	7.1
Overall %	*100.0*	*43.3*	*35.1*	*78.4*
Predictable	0.6	0.4	0.1	0.5
Overall %	*6.2*	*4.8*	*0.8*	*5.6*
Predictable %	*100.0*	*77.7*	*12.3*	*89.9*
Residual	8.4	–	–	–
Overall %	*93.8*	–	–	–
Residual %	*100.0*	–	–	–

Notes. PCA = principal component analysis. Values are variance in regular font and percentages of variance in italics for BADE scores. Total is based on the *Z* (overall) matrix. Predictable is based on the *GC* matrix (predicted scores) and Residual is based on the *E* matrix (error scores), but resulting from multivariate multiple regression of *Z* on *G* (External Analysis). Variance values from PCA on *Z* and *GC* are presented in the Internal Analysis columns, and variance values are the sum of the squared loadings from the rotated component loading matrices. The external analysis describes the output of the multivariate multiple regression of the Signs and Symptoms of Psychotic Illness (SSPI) symptoms predicting BADE scores. The internal analysis describes the output of the PCAs carried out on the *Z* (Overall) and *GC* (Predictable) matrices, but was not carried out on the *E* (Residual) matrix for simplicity of presentation. Percentage variance is displayed as a percentage of the total or predictable variance. Based on Hunter and Takane (2002).

Table 3. Component loadings for the overall (*Z*) solution. This is based on all variance in the BADE scores, resulting from simple PCA that does not separate variation predictable and not predictable from SSPI symptoms

BADE measure	Component 1 (Evidence integration)	2 (Response conservatism)
True (confirmatory evidence)		
First rating	0.24	**0.87**
Second rating	0.11	**0.88**
Third rating	**−0.39**	0.71
Lure (disconfirmatory evidence)		
First rating	0.35	**0.83**
Second rating	0.69	**0.55**
Third rating	**0.84**	0.03
Absurd (implausible information)		
First rating	**0.82**	0.31
Second rating	**0.92**	0.18
Third rating	**0.94**	0.04

Notes. BADE = bias against disconfirmatory evidence; PCA = principal component analysis; SSPI = Signs and Symptoms of Psychotic Illness. Expected dominant loadings based on past work for each interpreted component are set in bold font.

Table 4. Component loadings for the Predictable (*GC*) solution. These are the component loadings for the PCA based on variance in BADE items that was predictable from selected SSPI symptoms (i.e., correlations between *GC*-derived component scores and *GC*)

	Component	
BADE measure	1 (Evidence integration)	2 (Not interpreted)
True (confirmatory evidence)		
First Rating	0.04	0.09
Second Rating	−0.00	0.06
Third Rating	**−0.22**	**0.18**
Lure (disconfirmatory evidence)		
First Rating	0.08	0.03
Second Rating	0.13	−0.03
Third Rating	**0.23**	**−0.13**
Absurd (implausible information)		
First Rating	**0.33**	0.00
Second Rating	**0.33**	−0.01
Third Rating	**0.30**	−0.07

Note. PCA = principal component analysis; BADE = bias against disconfirmatory evidence; SSPI = Signs and Symptoms of Psychotic Illness rating scale. Dominant loadings for each component are set in bold font.

Table 5. Signs and Symptoms of Psychotic Illness (SSPI) predictor loadings onto the components of the Predictable (*GC*) solution. The predictor loadings describe which SSPI items are most related to derived components (i.e., correlations between *GC*-derived component scores and *G*)

	Component	
SSPI item	1 (Evidence integration)	2 (Not interpreted)
Delusions (SSPI 7)	**0.53**	0.30
Hallucinations (SSPI 8)	−0.16	**0.49**
Underactivity (SSPI 12)	−0.25	0.12
Flattened affect (SSPI 13)	−0.09	−0.35
Inappropriate affect (SSPI 14)	0.05	0.32
Poverty of speech (SSPI 16)	−0.47	**−0.75**
Thought disorder (SSPI 17)	**0.74**	−0.09

Note. SSPI = Signs and Symptoms of Psychotic Illness rating scale. Dominant loadings for each component in bold.

dominated by the third rating of true and lure interpretations, and all three absurd ratings. Component 2 showed a negative relationship between the third rating of the true and the third rating of the lure interpretation, but accounted for a very small percentage of variance (< 1% of total), so is not discussed further. Table 5 lists the predictor loadings, which are the most important statistics for relating SSPI symptoms to the BADE task components from *GC*. Tables 4 and 5 must be interpreted in conjunction, because they are different pieces of information about the same components; namely, they are the component loadings and the predictor loadings, which are computed as correlations between the *GC*-based component scores and the *GC* and *G* matrices, respectively. The predictor loadings (Table 5) show that delusions and thought disorder dominated the solutions and loaded in the same direction, demonstrating that increases in severity in both were related to poorer evidence integration.

Discussion

In the current study CPCA was used to clarify relationships between a cognitive task (the BADE task) and symptomology (SSPI scores). CPCA combines multivariate multiple regression with PCA, and was used to explore how the symptom profile of schizophrenia relates to BADE. This data-driven approach ensures that all derived components are optimized to be predictable from symptoms, and allows determination of how a range of symptoms relate to the BADE scores.

Component 1 of the predictable (*GC*) solution was interpreted as evidence integration (Sanford et al., 2014; Speechley et al., 2012) and revealed the relationship between impaired evidence integration in the BADE task and symptom combinations. Primarily, the increases in the severity of delusions and thought disorder predicted a decreased ability to integrate evidence. That is, the greater the severity of delusions and thought disorder, the higher participants rated lure and absurd interpretations, and the lower participants rated the true interpretation, once all information had been made available. This replicates previous findings of delusion severity being associated with the inability to effectively integrate new evidence (Sanford et al., 2014; Speechley et al., 2012; Woodward, Moritz, Cuttler, et al., 2006), but importantly, our results demonstrate a novel finding showing that the effect is not strictly specific to delusions, but extends to thought disorder. Thus, despite the well-replicated overlap between hallucinations and delusions (Liddle, 1987; Liddle et al., 2002; Rückl et al., 2011), hallucinations were not related to impaired evidence integration, suggesting a dissociation between delusions and hallucinations with respect to the BADE tasks and evidence integration.

A relatively small percentage of variance in BADE (i.e., 6.2%) was predictable from the SSPI symptoms. The permutation test shows that the observed variance accounted for by symptoms in BADE is reliable, and the effect size medium-to-small, with a medium effect size for variance accounted for being 9% (Pearson's r = 0.30, Cohen's d = 0.50) and a small effect size being 1% (Pearson's r = 0.10, Cohen's d = 0.20). This also indicates that over 90% of the BADE score variance cannot be predicted by symptoms. A split-half reliability assessment of the BADE task (not presented here, but involves splitting the BADE trials into sets A and B, and using set A in Z and set B in G, and carrying

out the external CPCA analysis) resulted in 85% variance overlap between split halves, so the low percentage of predictable variance in BADE cannot be explained by psychometrically unreliable measures in *Z*. Variables that may determine individual differences in BADE performance that are not predictable from symptoms could include intelligence, cognitive flexibility, response styles, personality traits, and/or individual past experiences, although intelligence and cognitive flexibility were mostly ruled out in past work (Woodward, Buchy, Moritz, & Liotti, 2007). Future investigations should focus on predicting variance in the analyses of the residual/error (*E*) matrix to better understand variance unrelated to symptomology. Since the BADE is one of the cognitive biases most consistently correlating with delusions in the literature, these results suggest that a small effect size will be a challenge to studies investigating the overlap between cognition and symptoms, as a similarly small effect size is likely pervasive in the field of cognitive neuropsychiatry (i.e., investigations into the overlap between cognition and symptoms; Halligan & David, 2001). Currently, this valuable statistic (a multivariate R^2) is rarely reported to our knowledge.

This exploratory analysis leads us to reflect on what may account for the association between delusions, thought disorder, and evidence integration. One starting point is brain imaging, because our research group has carried out functional magnetic resonance imaging (fMRI) studies on evidence integration and its relationship to delusions, and cognitive processes thought to underlie thought disorder. Evidence integration involves a functional brain network (computed with fMRI-CPCA software developed by our laboratory) that includes activations in the inferior frontal gyrus pars triangularis/Broca's area (Lavigne, Menon, & Woodward, 2018; Lavigne, Metzak, & Woodward, 2015), and reduced activation in this network is correlated with the evidence integration component from the behavioural BADE task (Lavigne, Menon, & Woodward, 2018). Thought disorder may also involve a language-based functional brain network (left middle temporal gyrus, inferior frontal gyrus pars triangularis/Broca's area) as it underpins controlled semantic integration processes (Woodward et al., 2015). We can speculate that the association between delusions, thought disorder, and evidence integration may be based on reduced coordinated activity in language-based functional brain networks, but further fMRI studies employing the BADE task and SSPI measures would be required to test and corroborate these hypotheses.

Conclusions

The original investigations into the BADE task indicated that delusional patients had reduced evidence integration, and in the current study we explored whether or not the effect is specific to delusions, or also extends to other symptoms. We replicated the finding that delusions are associated with evidence integration, but the results showed that thought disorder was also related to evidence integration. This isolation of BADE measures predictable from symptomology was optimized with CPCA, because it allowed separation of variance in BADE scores into that which was predictable and not predictable from symptoms as a starting point. This allowed for a broader view of the range of symptoms that are associated with the cognitive biases measured by the BADE task, while at the same time ensuring that the measured cognitive biases are optimally predictable from symptoms. Importantly, these methods make clear that while symptoms can reliably predict a proportion of variance in a cognitive task, the effect size is medium-to-small. This provides novel methodology for cognitive neuropsychiatric investigations (Halligan & David, 2001) into the cognitive underpinnings of the symptoms of schizophrenia by allowing investigators to consider a range of symptoms alongside the one that is the target of their investigation. This may lead to novel theoretical accounts, possibly putting forward more general cognitive processes underlying sets of symptoms in schizophrenia.

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