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A cognitive model of delusion propensity through dysregulated correlation detection

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ABSTRACT

Background: We present a novel account of delusion propensity that integrates the roles of working memory (WM), decision criteria, and information gathering biases. This framework emphasises the role of aberrant correlation detection, which leads to the spurious perception of relationships between one's experiences. The frequency of such outcomes is moderated by the scaling of one's decision criteria which, for reasons discussed, must also account for WM capacity. The proposed *dysregulated correlation detection* account posits that propensity for delusional ideation is influenced by disturbances in this mechanism.

Methods: Hypotheses were tested using a novel task that required participants ($N = 92$) to identify correlation between binary manipulations of simple shapes, presented as sequential pairs. Decision criteria and correlation detection were assessed under a Signal Detection Theory framework, while WM capacity was assessed through the Automated Operation Span Task and delusion propensity was measured using the Peters Delusion Inventory. Structural equation modeling was conducted to evaluate the proposed model.

Results: Consistent with the central hypothesis, an interaction between decision criteria and WM was found to contribute significantly to delusion propensity through its effect on correlation detection accuracy. Greater delusion propensity was observed among participants with more liberal decision criteria, which was also in accordance with hypotheses. At the same time, the total effect of WM on delusion propensity was not found to be significant.

Conclusions: These findings provide preliminary support for the proposed *dysregulated correlation detection* account of propensity for delusional ideation.

1. Introduction

Delusions are a core symptom of schizophrenia spectrum and other psychotic disorders (American Psychiatric Association, 2013). However, as with other psychotic experiences, delusional ideation is not confined to clinical populations (e.g., Verdoux and van Os, 2002). Continuum models of psychosis contend that clinically-significant delusions represent the severe expression of trait characteristics or stress reactions, to which individuals in the wider population are susceptible in varying degrees (Claridge, 1994; Costello, 1994; Meehl, 1990). Growing evidence supports such models, including systematic reviews of both hallucinatory and delusional phenomenology (Baumeister et al., 2017; van Os et al., 2009). To the extent that psychotic experience varies along a continuum, psychopathological symptoms may represent extreme presentations of common error tendencies. The phenomenon of "illusory correlation" is one such tendency that involves the perception of relationships where an association does not genuinely exist (Chapman, 1967). Given that the detection of correlation plays a central role in learning and reasoning (Perales and Shanks, 2007), systematic biases may logically contribute to the formation of belief structures that are incongruent with available evidence. The potential role of illusory correlation in psychosis is also supported by evidence suggesting that people with schizophrenia, and those with greater delusion propensity, are more susceptible to these perceptual errors (Balzan et al., 2013; van Prooijen et al., 2017). For this reason, correlation detection may represent a promising mechanism for understanding the aetiology of delusional ideation.

Cognitive models suggest that the strength of relationship between past experiences is evaluated based on the sampling of observed covariance from long-term memory (Griffiths and Tenenbaum, 2005;

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Holyoak and Cheng, 2011),while the capacity of one's working memory (WM) imposes a limitation on the number of prior experiences that may be considered (Hourihan and Benjamin, 2010; Vul et al., 2014). Within this framework, WM capacity constrains the size of samples (i.e., the number of past covariation events) available for consideration and may, therefore, create potential biases impacting one's conclusion. One factor that is likely to contribute such biases is the long-known skew that characterises the sampling distribution of correlation coefficients (David, 1954; Juslin and Olsson, 2005; Kareev, 2000). This skew has the effect that a larger proportion of finite samples provide over-estimates of correlation strength and this discrepancy is increased as sample size is reduced.

The skewed sampling distribution of correlation coefficients has interesting implications when considered in the context of WM limitations and the decision thresholds set by individuals when assessing non-zero correlations. Arithmetic simulations conducted by Anderson et al. (2005) found that accuracy in the identification of non-zero correlation (i.e., a "hit") improves with either an increase in sample size or when more conservative decision criteria are applied. Conversely, the risk of identifying a correlation where no such relationship exists (i.e., a "false alarm") increases when decisions are made using smaller samples or when decision-makers apply more liberal thresholds. Crucially, Anderson et al. (2005) identified an interaction between these variables (owing to the skewed sampling distribution), such that the effect of sample size on accuracy was more positive for decisions that were based on more liberal criteria. In comparison, the effect of sample size was attenuated for decisions that were based on more conservative criteria. In the event that decision criteria are excessively liberal relative to an individual's working memory capacity, accuracy in the detection of correlation may, therefore, be affected. This may result in an increased rate of false alarms and/or failure to correctly detect correlation (i.e., a "miss"). In this manner, delusional ideation may arise through the combination of reduced working memory capacity and liberal criteria in the detection of correlation.

Interestingly, research investigating delusion propensity has implicated both decision criteria and WM. Recent meta-analyses have demonstrated that data-gathering biases, including a tendency to make probabilistic inferences based on less information ('jumping to conclusions'; JTC; Huq et al., 1988), are associated with both the occurrence and severity of delusions (Dudley et al., 2016; Ross et al., 2015). The liberal acceptance hypothesis suggests that these stem from a tendency to set more liberal decision criteria in probabilistic reasoning, making determinations based on ambiguous information (Moritz and Woodward, 2004) or endorsing responses based on lower estimates of probability (Moritz et al., 2006). Research has suggested that data-gathering biases may also be associated with decrements in WM capacity among those experiencing delusions (Broome et al., 2007; Garety et al., 2013), and that cognitive remediation training may even serve to reduce such bias (Andreou et al., 2015). This is of particular relevance given that impaired WM is a well-established cognitive feature of schizophrenia (e.g., Horan et al., 2008). Significantly, Broome et al. (2007) found a relationship between WM and data-gathering biases in at-risk populations, while observing that poorer WM is associated with conservative response styles in healthy controls. These findings lend support to the notion that appropriate scaling of decision criteria may be necessary to adjust for WM limitations, and that failure to do so may result in heightened propensity for delusional ideation.

Illusory correlation may also be favoured as a key mechanistic substrate for its capacity to account for several phenomenological features of delusional ideation. For example, by disturbing one's perception of events directly, beliefs emerging as a result of illusory correlation are likely to be held with particularly strong conviction and limited insight. Interestingly, strength of conviction and lack of insight into the delusional nature of one's beliefs were identified by Miller et al. (2003) as key features distinguishing sub-clinical manifestations of psychotic experience from more fully-developed psychoses. The notion that delusional ideation is primarily a result of perceptual anomalies is also consistent with the influential theory put forward by Maher (1974). According to this, delusional ideation may emerge through logical reasoning applied to aberrant perceptions. A key tenet to this theory, and evidence in support of the role of perceptual disorder such as that of illusory correlation, is that beliefs which appear to be directly supported by one's experiences are likely to be less easily discredited through reasoning (Maher, 1988).

Disturbances in the detection of correlation may also be consistent with several common manifestations of delusional ideation. For example, the erroneous perception of a relationship between the contents of one's thoughts and the actions of another person may logically contribute to the belief that one's thoughts are audible to others or that one has special powers. Similarly, a series of improbable coincidences (i.e., correlations between one's experiences) may leave the impression that these events hold some special meaning (e.g., as an omen to the end world). As another example, the perception of a relationship between one's morally ambiguous actions and the incidence of negative events may result in the belief that these actions constitute sins for which one has been punished. It is therefore important that the potential role of illusory correlation is integrated with other factors associated with delusional ideation, including effects involving WM and data-gathering biases.

1.1. Aim and hypotheses

The present research aimed to investigate a new model of delusion propensity that incorporates the effects of both WM and decision criteria through aberrant correlation detection. The centrepiece of this model is a hypothesised moderation relationship between WM and decision criteria, which has the potential to influence delusion propensity through its effects on the detection of correlation. We propose that the application of decision criteria that are poorly calibrated to WM capacity, an effect we refer to as *dysregulated correlation detection*, may underpin propensity for delusions. To our knowledge, this is the first investigation to consider the interaction between WM and decision criteria as a precipitant of aberrant belief systems.

The study involved a novel task that was designed to assess participants' detection of binary correlation between shape pairs. Decision criteria and correlation detection accuracy were calculated under a Signal Detection Theory (SDT) framework, represented by Beta and the Area Under receiver operating characteristic Curves (AUC) respectively (see Stanislaw and Todorov, 1999). WM was measured using the Automated Operation Span Task AOSpan; Unsworth et al. (2005), while propensity for delusional ideation was assessed using the Peters Delusion Inventory (PDI; Peters et al., 2004).

It was hypothesised that lower correlation detection accuracy (i.e., AUC) would be associated with greater propensity for delusions (i.e., PDI scores). Poorer WM and more liberal decision criteria (i.e., Beta) were also hypothesised to be associated with higher scores on the PDI. It was anticipated that these relationships would be mediated by participants' correlation detection accuracy. A negative interaction was hypothesised between the effects of WM and decision criteria on accuracy in the detection of correlation. That is, the effect of WM on correlation detection accuracy was expected to be more positive for participants utilising liberal decision criteria. Through its effect on correlation detection accuracy, it was anticipated that delusion propensity would be influenced by this interaction also. These hypotheses are instantiated in the path diagram presented in Fig. 2.

2. Method

2.1. Participants

The initial sample included 141 participants recruited through the ANU Research School of Psychology's electronic participant recruitment system. Participants were predominantly undergraduate students, who were granted course credit toward psychology or computer science units. Several pre-selected exclusion criteria were applied, as outlined in the *Materials and Design* and *Statistical Analyses* sections. After screening and data cleaning, the final sample consisted of 92 participants (68 females; see *Supplementary Material* for additional demographic information). Given the model's relatively small number of variables and its focus on observed indicators (Wolf et al., 2013), the sample size was considered appropriate for the intended analysis.

2.2. Materials and design

2.2.1. Background questionnaire

In addition to basic demographic information, the background survey canvassed vocabulary comprehension by requiring participants to select, from four possible responses, synonyms for words contained in the PDI. A total of 23 participants answered one or more of these questions incorrectly and were excluded from the analysis. Participants were also considered for exclusion if they indicated that their English language ability was below 'Intermediate (e.g. can understand a wide variety of everyday words)' or they did not have normal (or corrected-to-normal) vision and intact colour vision. No exclusions were necessary on these grounds.

2.2.2. Substance abuse screening instruments

The Drug Abuse Screening Test (DAST-10; Cocco and Carey, 1998; Yudko et al., 2007) and the Short Michigan Alcoholism Screening Test (SMAST; Selzer et al., 1975) were used to exclude participants based on self-reported indications of substance misuse. A total of 11 participants scored in a range suggestive of drug abuse on the DAST-10 (i.e., >3; Bohn et al., 1991), and were excluded from further analysis. Consistent with the threshold (i.e., >5) recommended by Barry and Fleming (1993), a further two participants were excluded based on SMAST scores.

2.2.3. Peters delusion inventory

The PDI is a 21-item inventory designed to assess propensity for delusional ideation in the general population (Peters et al., 2004). The inventory has good internal consistency ($\alpha = 0.82$) and test-rest reliability ($r = 0.78$), as well as construct and criterion validity (Peters et al., 2004). It includes 21 binary (yes/no response) items that require participants to identify whether they hold beliefs considered to be indicative of delusional ideation. For positively endorsed items, participants are asked to identify the level of distress it causes, the frequency of its occurrence and the extent to which they believe it is true. These additional dimensions involve three separate five-point Likert scales. Subscales may be derived by summing the scores on items reflecting distress ($PDI_{distress}$), preoccupation ($PDI_{preoccupation}$), and level of conviction ($PDI_{conviction}$; i.e., a score between 0 and 105 on each). Two additional subscales can be developed to provide a more global indication of delusion propensity. These include a simple sum of binary items on which participants identified having experienced a belief (PDI_{21}; i.e., a score between 0 and 21), and a measure that combines each of the other subscales (i.e., a score between 0 and 336). For parsimony, the present study focussed on this aggregate scale given its stronger reliability (Peters et al., 2004) and the research interest in global propensity for delusional ideation. Unless otherwise specified, references to PDI refer to this aggregate scale.

2.2.4. Automated operation span task

The AOSpan is a measure of WM capacity developed by Unsworth et al. (2005). It is an extension of the operation span (OSpan) task introduced by Turner and Engle (1989), and requires participants to memorise items of information interspersed with distracting activities (e.g., Case et al., 1982; Daneman and Carpenter, 1980; Shah and Miyake, 1996; Turner and Engle, 1989). The AOSpan asks participants to memorise a series of letters, which are separated by questions involving simple arithmetic computations and requiring participants to identify whether a given answer is true or false. Consistent with recommendations (Unsworth et al., 2005), six participants that did not meet the 85% accuracy criterion were excluded from further analysis.

2.2.5. Experimental correlation detection task

The *correlation detection task* involved sequential presentation of pairs of two different shapes. While each shape was always presented in the same colour to support recognition, a binary manipulation meant that they could be either filled or hollow on any single presentation (see Fig. 1). Correlation between the appearance of shapes (i.e. whether filled or hollow) was established across sequential presentations. Each trial included 28 pairs of a single shape combination. Shape combinations were changed across trials, such that all possible combinations of blue circles, yellow squares, red triangles, and green stars were used. Stimuli were presented for 400 ms and separated by a Gaussian white noise mask lasting 100 ms (see Fig. 1). As such, each trial lasted 14 s. The correlation task involved a total of 60 trials, including 30 with correlations of zero and 30 containing non-zero (positive) correlations. There were three non-zero correlation strengths, each presented in 10 separate trials, with phi correlation coefficients (Φ) equal to 0.07, 0.29 and 0.43 (see *Supplementary Material* for an extended description of the correlation task parameters and procedure).

Following each trial, participants were asked to use a 6-point rating scale to indicate whether they believed that the appearance of the shapes was correlated (i.e., either positively or negatively). The lower and upper points of the scale were labelled "Definitely not correlated" and "Definitely correlated", respectively. Participants were asked to use the central threshold (between points 3 and 4) to indicate whether they believed a correlation existed or not.

2.3. Procedure

All surveys and both cognitive tasks were administered using Inquisit 5 (Inquisit 5, 2017). Participants were seated for the duration of the experiment, approximately 60 cm from the 120 Hz computer monitor. Each participant completed testing over a period of approximately 1 h at computer terminals in separate rooms, with natural light supplemented by fluorescent illumination. Participants were required to complete the background questionnaire, followed by the PDI. Two further segments of the experiment were counter-balanced across participants. The first included completion of the AOSpan task. The second included four separate blocks of 15 correlation task trials, separated by the SMAST, DAST, and two other self-report questionnaires assessing personality and psychopathology (see *Supplementary Material*).

2.4. Statistical analyses

Participants' decision criteria and correlation detection accuracy were assessed within an SDT framework. Decision criteria (Beta), which represent each participant's tendency to indicate the presence or absence of a relationship (Stanislaw and Todorov, 1999), were calculated. In the present context, setting a lower decision criterion would result in more liberal acceptance of correlation. The central threshold (i.e., between points 3 and 4) was used as the basis for calculating Beta parameters. While trials varied with respect to the strength of correlation (i.e., zero correlation and three strengths of non-zero correlation), these were treated in a binary manner (i.e., signal present or absent) in accordance with the SDT framework (see Stanislaw and Todorov, 1999). On the correlation detection task, six participants returned either zero hits or zero false alarms. In addition to reflecting poor concentration on the activity (i.e., for those returning zero hits), limitations of the probit function meant that Beta scores were not able to be calculated for these participants. Data from these six participants were, therefore, excluded from further analyses.

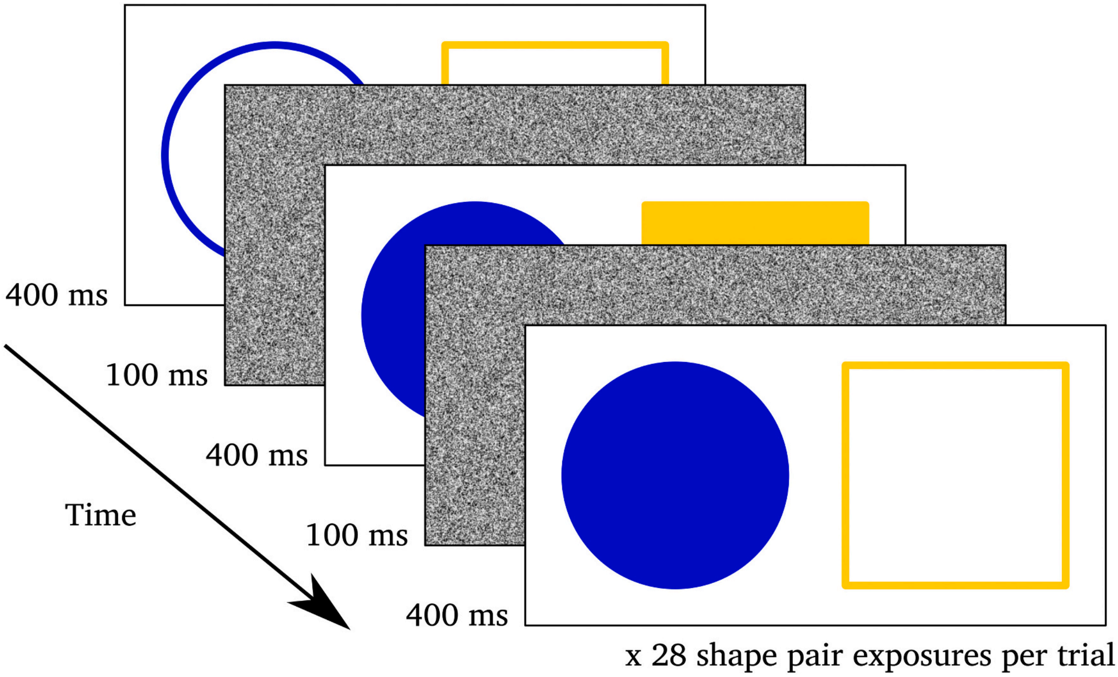

Fig. 1. Schematic representation of visual stimuli presented during correlation task trials.

Responses to the rating task were also used to calculate Receiver Operating Characteristics (ROC) curves, which plot hit (H) against false alarm (F) rates. The area under a ROC curve (AUC) provides a measure of accuracy in the detection of binary variables that is mathematically independent of decision criteria (Stanislaw and Todorov, 1999). ROC curves were calculated using the upper three thresholds (i.e., between points 3, 4, 5 and 6 on the rating task), so as to reflect the accuracy and confidence with which correlation was detected. For a detailed treatment of SDT theory and parameter calculations, see Stanislaw and Todorov (1999).

Statistical analyses were carried out in IBM SPSS Statistics 25 and the AMOS Graphics extension. Descriptive analyses sought to characterise the sample and correlation between variables prior to model development. One participant was identified as a multivariate outlier (i.e., among modelled variables), based on a Mahalanobis distance threshold of $p < .001$ (as recommended by Tabachnick and Fidell, 2014), and therefore excluded from further analysis. Modest skew was identified in the WM and PDI variables, based on visual inspection of histograms and skewness statistics (−0.389 and 0.704, respectively). To improve the model's robustness, negative skew in the distribution of WM scores was corrected by a squaring transformation and the positive skew of PDI was corrected by taking the square root. Transformation reduced skewness statistics of both WM and PDI (to 0.231 and 0.007, respectively) prior to entry into the model.

To test hypotheses, a confirmatory path analysis was conducted using bootstrap estimation. In particular, confidence intervals and significance tests of the path coefficients, indirect and direct effects were estimated using the bias-corrected bootstrap percentile method (2000 samples). The structural model is represented in.

3. Results

3.1. Descriptive statistics

Descriptive statistics for modelled variables are presented in Table 1. With regard to demographics, participant age (years; $M = 20.7$, $SD = 2.1$) was not found to correlate with PDI ($r = -0.105$, $p = .320$), WM ($r = -0.030$, $p = .778$) or AUC ($r = 0.164$, $p = .118$). A small to moderate

Table 1
Descriptive statistics.

Descriptive statistics	Beta	WM	AUC	PDI
Mean	0.97	46.51	0.63	60.02
Standard deviation	0.40	16.56	0.12	38.96
95% CI				
Lower bound	0.89	43.08	0.60	51.95
Upper bound	1.05	49.94	0.65	68.09
Median	0.98	49.50	0.62	52.50
Minimum	0.19	9.00	0.24	4.00
Maximum	3.07	75.00	0.88	189.00

Zero-order correlations of modelled variables	Beta	WM	WM × Beta	AUC
Beta				
WM	−0.088			
WM × Beta	−0.024	0.020		
AUC	0.095	0.075	−0.212*	
PDI	−0.355**	0.203	−0.018	−0.238*

Standardised regression coefficients		Independent variable			
		Beta	WM	WM × Beta	AUC
Total effects	AUC	0.098	0.088	−0.211*	
	PDI	−0.339**	0.172	0.047*	−0.222*
Direct effects	AUC	0.098	0.088	−0.211*	
	PDI	−0.317**	0.191		−0.222*
Indirect effects	AUC				
	PDI	−0.022	−0.019	0.047*	

Note. Beta = decision criteria, WM = Working Memory, AUC = Area Under Curve (correlation detection accuracy), and PDI = Peters Delusion Inventory. Descriptive statistics represent WM and PDI variables prior to transformation, while zero-order correlations, regression coefficients and tests of significance were based on transformed distributions for improved robustness (see *Statistical Analyses*).

* $p < .05$.

** $p < .01$.

positive correlation was observed between age and Beta ($r = 0.283$, $p = .006$), suggesting that older participants applied more conservative decision criteria. Cronbach's alpha indicated strong internal consistency on the PDI ($\alpha = 0.88$), similar to levels previously recorded ($\alpha = 0.82$; Peters et al., 2004). An appropriate range of scores were observed across the different subscales, including the global PDI measure ($M = 60.02$, $Md = 52.50$, $SD = 38.96$, min = 4, max = 189), as well as PDI_{21} ($M = 6.37$, $Md = 6.00$, $SD = 3.46$, $min = 1$, $max = 15$), $PDI_{distress}$ ($M = 16.30$, $Md = 14.50$, $SD = 11.23$, $min = 1$, $max = 52$), $PDI_{preoccupation}$ ($M = 17.30$, $Md = 14.50$, $SD = 12.34$, $min = 1$, $max = 64$) and $PDI_{conviction}$ ($M = 20.04$, $Md = 17.50$, $SD = 13.10$, $min = 1$, $max = 58$).

3.2. Model estimation

The hypothesised model was found to have strong fit and did not differ significantly from the saturated model (i.e., one in which all parameters are estimated for every variable, including covariance between each), $\chi^2(1) = 0.693$, $p = .405$. Given that the χ^2 statistic was less than the degrees of freedom, representing a very strong fit, the Root Square Error of Approximation (RMSEA) was approaching zero (Chen et al., 2008) and the Comparative Fit Index (CFI; Bentler, 1990) was approaching 1.000. Model fit was also checked using the 'lavaan' package in R (Rosseel, 2012). Regression coefficients of the specified model are presented in Fig. 2 and Table 1.

Because the direct effect of WM on PDI was not found to be significant, the model was compared against a specification that removed this path. The exploratory comparison model ($\chi^2(2) = 4.719$, $p = .094$, CFI = 0.848, RMSEA = 0.122) demonstrated a significant reduction in goodness of fit compared with the hypothesised model, $\Delta\chi^2\ (1) = 4.026$, $p = .044$, supporting retention of the direct path parameter. It is noteworthy that the zero-order correlations revealed no significant correlation between the WM × Beta interaction and PDI. This is consistent with a moderated mediation relationship, given that this involves moderation of the mediation path effects. A correlation between the WM × Beta interaction and PDI may instead reflect mediation of a moderated relationship.

3.3. Direct effects

Both Beta ($\beta = -0.317$, 95% CI [−0.506, −0.110], $p = .003$) and correlation detection accuracy (AUC; $\beta = -0.222$, 95% CI [−0.426, −0.004], $p = .046$) were observed to have significant direct negative relationships with delusional ideation (PDI). In support of our hypothesis, the direct negative relationship between Beta and PDI suggested that more liberal decision criteria were associated with greater delusion propensity. AUC was not significantly associated with either Beta ($\beta = 0.098$, 95% CI [−0.099, 0.275], $p = .317$) or WM ($\beta = 0.088$, 95% CI [−0.137, 0.281], $p = .480$) independently of one another. In contrast, and consistent with our hypotheses, AUC was significantly predicted by an interaction between these variables (WM × Beta; $\beta = -0.211$, 95% CI [−0.392, −0.000], $p = .050$; see Fig. 3A). Consistent with hypotheses, the nature of this interaction was such that individuals with smaller WM capacity demonstrated poorer detection of correlation when this was combined with a propensity for liberal decision criteria. Contrary to our hypothesis that delusion propensity would be associated with reduced WM capacity, the direct relationship between WM and PDI was not found to be significant ($\beta = 0.191$, 95% CI [−0.008, 0.397], $p = .062$).

To investigate the relative contribution of H and F to lower accuracy among those with greater propensity for delusional ideation, zero order correlations were calculated. These assessed the correlation between each participant's PDI score and the rate of hits and false alarms recorded at each Likert scale threshold. PDI scores were not correlated with hit rates across the threshold between points 3 and 4 ($r = 0.013$, $p = .899$), points 4 and 5 ($r = 0.018$, $p = .863$), and between points 5 and 6 ($r = -0.008$, $p = .951$). In contrast, significant positive correlations were observed between PDI scores and the rate of false alarms observed between points 3 and 4 ($r = 0.316$, $p = .002$), points 4 and 5 ($r = 0.310$, $p = .003$), and points 5 and 6 ($r = 0.330$, $p = .001$). These results suggest that lower rates of accuracy in the detection of correlation (AUC) among those more prone to delusional ideation were driven primarily by higher incidence of false alarms. These differences are depicted in Fig. 3b which, for illustrative purposes, presents data dichotomised into groups with higher rates of delusional ideation (PDI_{21} Total Score > 8; $n = 35$) and lower rates ($n = 59$), based on the threshold recommended by Preti et al. (2007).

3.4. Indirect effects

PDI was not significantly predicted by the indirect effects of either WM ($\beta = -0.019$, 95% CI [−0.094, 0.025], $p = .282$) or Beta ($\beta = -0.022$, 95% CI [−0.098, 0.014], $p = .208$) through AUC. However, the indirect effect of WM × Beta was found to be statistically significant ($\beta = 0.047$, 95% CI [0.001, 0.124], $p = .042$). Consistent with hypotheses, the nature of this effect was such that individuals with smaller WM capacity demonstrated greater delusion propensity (i.e., PDI scores) when this was combined with a propensity for liberal decision criteria.

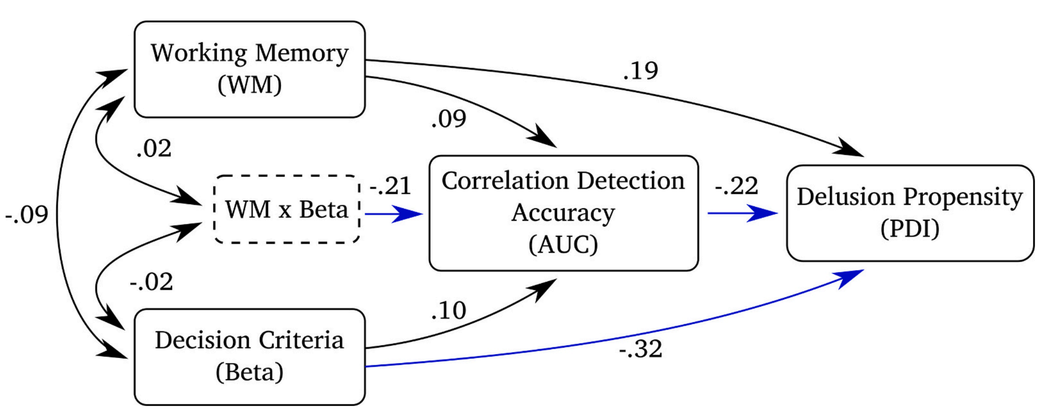

Fig. 2. Estimated model specification, demonstrating the influence of an interaction between decision criteria and WM on delusion propensity through its effect on correlation detection accuracy. Blue lines indicate the relationships that were found to be statistically significant ($p < .05$). A significant negative relationship between Beta and PDI reflected a tendency for people with higher levels of delusional ideation to demonstrate more liberal thresholds for identifying correlation. A significant negative relationship between the WM × Beta interaction and AUC indicated that the relationship between WM capacity and correlation detection accuracy was more positive among individuals that set liberal decision criteria. At the same time, a significant negative relationship between AUC and PDI suggested that individuals demonstrating lower accuracy in the detection of correlation reported higher levels of delusional ideation. (For interpretation of the references to colour in this figure, readers are referred to the web verion of the article.)

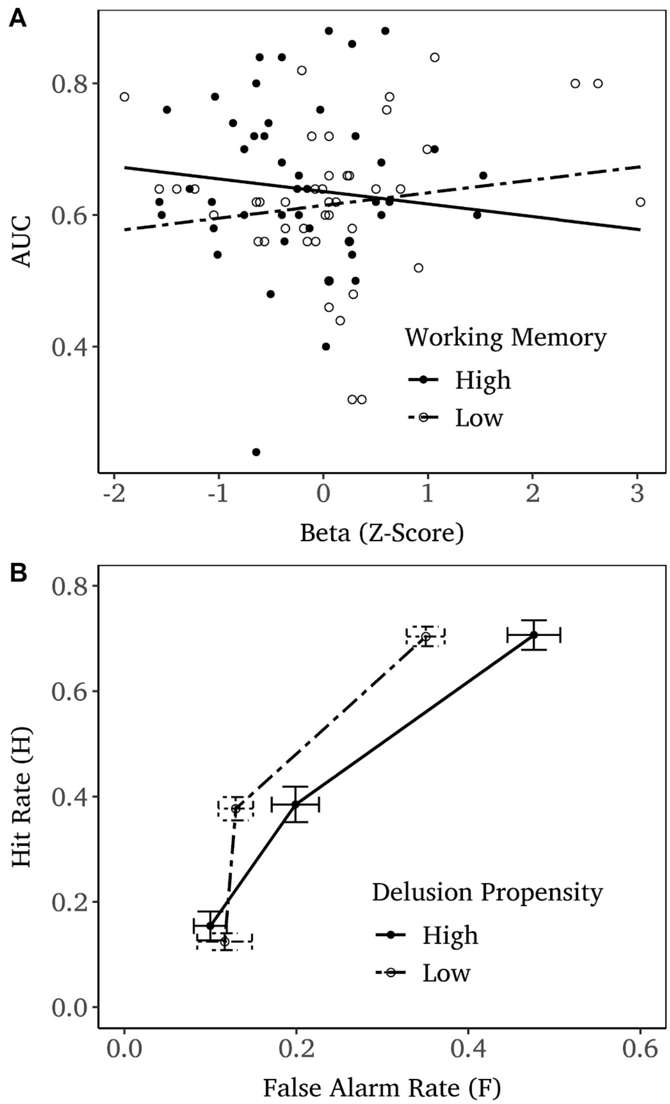

Fig. 3. A. WM moderation of the relationship between decision criteria (Beta) and accuracy in correlation detection (AUC). High and low WM groups represent a median-split by AOSpan score. B. ROC curves by delusion propensity (dichotomised based on PDI, see Preti et al., 2007), demonstrating hit and false alarm rates (as well as their standard errors) across three thresholds of the correlation rating task. Differences in correlation detection accuracy appear to be driven by higher false alarm rates among those more prone to delusional ideation.

3.5. Total effects

The total effect of Beta on PDI was found to be statistically significant ($\beta = -0.339$, 95% CI [−0.519, −0.118], $p = .002$), while the total effect of WM on PDI was not ($\beta = 0.172$, 95% CI [−0.029, 0.376], $p = .101$). Other total effects have been included in Table 1 for completeness. Given that these relationships involved *either* a direct or indirect path, their statistical significance is interpreted in the same manner as reported under relevant sections above.

4. Discussion

Results were consistent with the hypothesised *dysregulated correlation detection* account of delusional ideation, suggesting that aberrations in correlation detection may contribute significantly to the formation of belief systems that are incongruent with available evidence. As anticipated, lower accuracy in the detection of correlation was found to be associated with increased propensity for delusional ideation. Results from follow-up analyses suggested that the negative relationship between correlation detection accuracy and delusion propensity is driven primarily by higher rates of false alarm. This finding corroborates research conducted by Balzan et al. (2013), which found a relationship between illusory correlations and delusion propensity. While Balzan et al. (2013) attributed higher rates of false alarms to the hypersalience of evidence that is consistent with existing beliefs, use of neutral stimuli in the present study suggest that delusion propensity may be associated with such error tendencies whether or not stimuli are associated with prior expectations.

In accordance with the liberal acceptance account of delusion-related biases in information gathering (Averbeck et al., 2011; Moritz and Woodward, 2004), more liberal decision criteria were found to be associated with increased propensity for delusional ideation. The main effect of decision criteria on accuracy in the detection of correlation, and the indirect relationship between decision criteria and delusion propensity through correlation detection accuracy, were not significant. This outcome is contrary to simulations conducted by Anderson et al. (2005), which suggested that more liberal decision criteria would ordinarily be associated with an increased rate of false alarms relative to hits. Rather than a simple mediation relationship, results therefore suggested that the effect of decision criteria on correlation detection accuracy occurs primarily in the context of its interaction with one's WM capacity.

Although causal structures are not directly elucidated in the current model, the nature of this interaction is an important subject for theoretical consideration. For example, it seems likely that decision criteria are applied by individuals based on a variety of contextual factors, while WM remains fixed at one's capacity or is constrained by competing demands. To minimise the probability of missing a non-zero correlation, decision criteria are likely to be set at the most liberal level afforded by WM while also maintaining an appropriately low level of false alarms. In this context, metacognitive processes may calibrate decision criteria based on individual differences in WM capacity, or the level an individual is able to apply in situations with competing demands. Thus, propensity for delusional ideation may be associated with miscalibration of decision criteria in the context of WM limitations, and the resulting dysregulated error in the detection of correlation.

Our *dysregulated correlation detection* model is congruent with the two-factor theory of delusional belief developed by Langdon and Coltheart (2000), which contends that delusions are associated with a combination of perceptual anomalies and deficits in the evaluation of beliefs. While the two-factor model has demonstrated merit in accounting for the nature of different classes of delusional belief through distortions in perception (Coltheart et al., 2011), it has not yet empirically accounted for the proposed deficits in evaluation processes. Results from the present study may help address this issue, with a potential impediment to evaluation presenting in the form of *dysregulated correlation detection* through aberrant scaling of decision criteria.

The proposed framework also has parallels in research exploring metacognitive regulation of memory recall. On recall tasks, individuals appear to regulate their responses based on an implicit awareness of their own memory limitations (Koriat and Goldsmith, 1996). Given that the detection of correlation involves a process of sampling from probabilistic representations stored in long-term memory (Griffiths and Tenenbaum, 2005; Holyoak and Cheng, 2011; Hourihan and Benjamin, 2010; Vul et al., 2014), a similar metacognitive regulation may be applied to this process based on WM limitations. Metacognitive deficits pertaining to memory function also complement observed distortions in conscious awareness of memory performance in patients with schizophrenia, including memory confidence (Koren et al., 2004; Moritz and Woodward, 2004; Moritz et al., 2005), feeling-of-knowing (Bacon et al., 2001), and awareness of cognitive deficits (Grange et al., 1995; Moritz et al., 2004a, 2004b).

The study contained several limitations. Foremost among these was the recruitment from a non-clinical population, which impedes inference of the model across the full spectrum of delusion severity. Future research should seek to evaluate the dysregulated correlation detection framework among individuals with clinically-significant delusional ideation. Conceptual replication among clinical and non-clinical populations may also serve to address statistical limitations of the present investigation, including those arising through use of SDT and bias-corrected bootstrap estimation. Moreover, research has demonstrated that miscomprehension is common in probabilistic reasoning tasks and that worse performance among schizophrenia patients may be partially attributable to poorer understanding of such tasks (Balzan et al., 2012). While it is possible that those more prone to delusional ideation were more likely to have miscomprehended the correlation task, this is considered unlikely given the measures taken to ensure adequate understanding (including a detailed description, examples and practice trials). Moreover, research that has examined the influence of miscomprehension in the JTC effect has not revealed a significant difference between delusion-prone and non-delusion-prone participants (Balzan et al., 2012). Another important limitation relates to the distinction between accuracy and confidence in the detection of correlation. Past research has demonstrated that cognitive abilities (e.g., correlation detection accuracy and decision criteria) may vary independently from meta-cognitive assessments (e.g., evaluation of one's correlation detection accuracy; see Koriat and Goldsmith, 1998). While participants' confidence in their correlation detection was likely to be reflected in their decision criteria and accuracy, this was not explicitly examined in the present investigation. Future research might therefore be needed to explore the relative contribution of meta-cognitive factors, such as confidence, to the observed relationship between correlation detection and delusional ideation.

5. Conclusions

In conclusion, findings from the present study have unified existing accounts of propensity for delusional ideation with an integrated and compelling framework that considers the effects of WM, decision criteria and information gathering biases. Results suggest that, by influencing correlation detection accuracy, an interaction between decision criteria and WM contributes significantly to one's propensity for delusional ideation. The study has provided promising indications for a new etiological understanding of aberrant belief systems that integrates phenomenological features with cognitive and neuropsychological observations. Given the wide range of conditions in which delusional ideation manifests, a richer understanding of its drivers and therefore strategies to treatment may improve quality of life for many.

Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.schres.2021.08.025.

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