Quantifying the Latent-Cause Inference Process and Its Relationship With Schizotypy

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This paper represents my own work in accordance with University regulations.

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Abstract

Latent-cause inference is a process through which humans determine the hidden (latent) causes of events. Aberrant latent-cause inference could lead to suboptimal interpretation of causality, characteristic of certain psychopathologies like schizotypy or schizophrenia-spectrum disorders. In this study, data from N=565 subjects were analyzed. Subjects responded to a subset of questions from the Personality Inventory for DSM-5 that assessed schizotypal traits, and completed the “Microbes Task” – a clustering task developed to quantify latent-cause inference in humans. Four individual-level parameters were derived by fitting a Bayesian model of latent-cause inference to the Microbes Task data. It was hypothesized that higher schizotypy scores would be positively associated with a higher tendency to create new clusters, as well as a higher propensity to create wider clusters, indicative of a fractured and incoherent interpretation of the causal relationships between events. This hypothesis was borne out when schizotypy scores were treated as a categorical variable. However, when the schizotypy scores were analyzed as a continuous variable, only the propensity to create wider clusters was found to correlate significantly with schizotypy scores. Regression analysis was performed on subscale scores, yielding significant correlations between at least one latent-cause inference parameter and the subscales “Suspiciousness,” “Perceptual dysregulation,” and “Unusual beliefs & experiences.” These are the three subscales that assess “positive” schizotypal traits, which correspond to the positive symptoms of schizophrenia. These findings suggest that schizotypy and other conditions with a proneness to psychosis may involve carving the world into too many clusters or latent causes, offering a new theoretical understanding of cognitive deficits in schizophrenia-spectrum disorders.

Introduction[1]

Humans are remarkable in their capacity to interpret the world in a way that allows them to best learn from their experiences. One theory that explains how humans make sense of their environment is the latent-cause inference theory, first developed to explain classical conditioning in rodents (Gershman et al., 2010). In brief, this theory suggests that in studies of classical conditioning there is a latent (hidden) cause that underlies both the stimulus and reinforcement, so that learning the association between stimulus and reinforcement involves inferring this latent cause. Research has suggested that humans rely on latent-cause inference in many areas of life, ranging from understanding sensory experiences to making complex social decisions (Shin & Niv, 2021). In theory, normative inference of latent causes would correspond to inferring the actual causal structure in the world, supporting optimal generalization across experiences that have the same underlying cause. This could facilitate successful learning, memory, attention, and other cognitive processes. In contrast, a deviation from normative inference of latent causes could underlie psychopathology.

One psychopathology dimension that could be conceptualized as non-normative latent-cause inference is schizotypy, a dimensional construct ranging from normal mental states to psychosis (Morgan et al., 2009). Another way of looking at schizotypy is as a cognitive vulnerability towards psychosis within the neurotypical range (Peters et al., 1994). One fact that illustrates this perspective is that people high in schizotypy form unusual beliefs based on little evidence, which is conceptually similar to a tendency to assign new experiences to new latent causes, leading to segmenting (grouping) these experiences into too many causes. People high in schizotypy also show perceptual anomalies such as not being able to tell the difference between dreams and waking life (Krueger et al., 2012), which might impair their ability to distinguish between stimuli when assigning them to latent causes.

[1] This section contains text that is based closely on, or identical to, text found in my junior paper.

The motivation to pursue this research was to integrate existing cognitive and clinical findings about schizotypy under the latent-cause inference theory, which could help to better understand a wide range of disorders on the schizophrenia spectrum. This research also has potential practical implications: if severity of schizotypy could be correlated with performance on a latent-cause inference task, this task could be used for measuring schizotypy without relying on self-report.

In schizophrenia, there are three types of symptoms – positive, negative, and cognitive (National Institute of Mental Health, 2020). These three categories can also be applied in the context of assessing schizotypal traits. Positive symptomatology encompasses behavior and thought patterns that are not normally present in a neurotypical individual, such as paranoia, delusions, hallucinations, and other forms of unusual thinking and behavior. Negative symptoms usually involve a loss of behaviors and thoughts normally expected from a neurotypical individual. Negative symptoms include loss of interest or motivation, social withdrawal, anhedonia, and less emotional expression. Cognitive symptoms belong to a third category of symptomatology and include interferences with memory, concentration, and attention, leading to difficulties in retaining information, completing tasks, and even holding conversations (National Institute of Mental Health, 2020).

Another prominent cognitive characteristic of schizotypy is aberrant latent inhibition. Latent inhibition refers to the finding that a novel stimulus enters into new associations more readily than a stimulus that was encountered before (as cited in Höfer et al., 1999). It has been reported that people high in schizotypy have *reduced* latent inhibition (Höfer et al., 1999, Wuthrich et al., 2001, Ettinger et al., 2015). Reduced latent inhibition in schizotypy could be explained by over-segmentation of experiences into an excessive number of latent causes. In other words, people high in schizotypy might be more likely to attribute a familiar stimulus to a new latent cause and, therefore, not show any inhibition in entering that stimulus into a new association.

Multiple studies also report that people with schizotypy and schizophrenia perform poorly on categorization tasks. One study found that people with higher schizotypy perform worse on a semantic categorization task than a low schizotypy group (Morgan et al., 2009). This semantic categorization task requires participants to verify membership of a word in a group. The words can have varying degrees of typicality (relatedness) to this group. For example, “car” is more related to the group “vehicle” than “ferry” because “ferry” is less frequently encountered by an average individual. People from the high schizotypy group are less likely to put low-typicality members of the category into the corresponding category (i.e., less likely to say that ferry belongs to the category vehicle). This finding may support the hypothesis that people with schizotypy are more likely to under-generalize and infer more latent causes/categories in the world.

Much of the extant research focuses on people with schizophrenia rather than schizotypy. This research is nevertheless relevant to the current research question because it has been reported that healthy participants with high schizotypy scores demonstrate performance on cognitive tasks that is similar to performance of people with schizophrenia (Peters et al., 1994). In addition, as mentioned before, schizotypy is considered a vulnerability factor for schizophrenia (Lenzenweger, 2010). While individuals with high schizotypy are considered part of normal neurodiversity, these individuals exhibit a proneness to psychosis (Morgan et al., 2009), which comprises all the positive symptoms of schizophrenia, e.g., delusions and hallucinations.

Interestingly, it has been suggested that people with schizophrenia have a tendency to both over-generalize and under-generalize. For example, one study found that the majority of participants with schizophrenia generate abnormal categories during a semantic categorization test, the Category Generation Test (CGT) (Doughty et al., 2009). During the CGT, participants were given cards with drawings that belong to one of five categories – animals, fruit, body parts, clothing, and transport – and were asked to categorize them. Participants with schizophrenia often made “underinclusion” errors, which is when items from the same category are sorted into different piles (for example,

a dress was sorted separately from the rest of the clothing cards). This finding supports the hypothesis that people with schizotypy are likely to over-segment categories, i.e., infer many latent causes. People with schizophrenia also made “overinclusion” errors, which is when items from different categories are sorted together (for example, categorizing a monkey together with the fruit cards), suggesting that people with schizotypy might generate wide and over-generalized latent causes.

People with schizotypy and schizophrenia may also have difficulty discerning boundaries of categories. In one study, participants performed a categorization task in which they listened to a soundtrack of sounds made with different materials (wood, metal, and glass) that progressively transitioned between the three materials, and they then had to identify the material (Micoulaud-Franchi et al., 2011). Participants with schizophrenia perceived smoother transitions between categories of materials than control participants. In other words, participants with schizophrenia had a harder time determining the boundaries of the categories of sounds than control participants. Likewise, it is expected that people with schizotypy will be more likely to create wider categories, i.e., latent causes.

It is also suggested that people with schizophrenia are more likely to group things that are very different from each other and would be categorized into different groups by a neurotypical person. This was observed in one study, in which participants were asked to categorize words based on their semantic relatedness (Hui et al., 2012). Participants with schizophrenia assigned more semantically-dissimilar words to the same category than did controls. This finding supports the hypothesis that people with schizotypy may assign variable items to a single category, making them more likely to generate wider latent causes.

In light of these findings, we hypothesized that schizotypal traits would be associated with aberrant latent-cause inference, indicative of a fractured and incoherent interpretation of the causal relationships between events. We intuited that a high score on the subscale assessing “Unusual beliefs & experiences” would have the strongest

relationship with latent-cause inference. More specifically, we hypothesized that a person who scores high on this subscale would potentially have a higher propensity to under-generalize (over-segment) latent causes in some situations and over-generalize latent causes in other situations.

The intuition for our hypothesis can be illustrated with the following hypothetical situation. Imagine the sound of something heavy falling from the roof during the winter. A person is left to infer the cause of this sound. A neurotypical person may attribute the latent cause of the sound to snow sliding off the roof, which often happens during the winter. However, a person with a higher score on “Unusual beliefs & experiences” may attribute the sound to something more unusual, like a person who jumped with a parachute just landed on the roof and then slid off.

Another hypothetical scenario – a person forgets his watch and forgets the name of his coworker in one morning. A neurotypical person may attribute forgetting the watch to running late to work (one latent cause) and forgetting the coworker’s name to his limited interactions with that person (another latent cause). However, a person with a higher score on “Unusual beliefs & experiences” could be more likely to create over-generalized latent causes. This aberration in latent-cause inference may lead the person to attribute both of these events to having a rare disease that is worsening his memory (one latent cause) even though that is a less likely explanation for these two events.

In conclusion, while people who score high on schizotypal traits are described as lying on the spectrum of neurotypical diversity, high schizotypy scores indicate a vulnerability to exhibiting schizophrenia-like traits. Given the research findings cited above, we hypothesized that higher schizotypy scores would correlate with aberrant latent-cause inference processes. While the research presented in this paper provides only correlational evidence, it is not far-fetched to suggest that aberrant latent-cause inference may be underlying many of the schizotypal traits, especially the positive symptoms. Thus, this is an exciting research direction that may aid in better

understanding cognitive characteristics of people with schizotypal traits as well as people with schizophrenia-spectrum disorders.

Methods[2]

Participants

Data were collected by graduate student Dan-Mircea Mirea. Participants were recruited online through the website Prolific Academic. Data from subjects that failed more than the allowed number of attention checks were not included in the analysis. Data from N=565 subjects (gender: 328 female, 215 male, 22 nonbinary/unknown; age: mean = 33, range = 64) were used in the analysis. In addition to behavioral data (performance on the Microbes Task, see below) and self-report assessment of schizotypal traits (responses to a self-report questionnaire), basic demographic data were collected (age and gender). Participants were also asked to complete a symmetry span task, used to obtain data on their working memory. (Performance on a symmetry span task is a measure of working memory as cited in Unsworth & Engle, 2008).

The Microbes Task

In order to quantify the latent-cause inference process in humans, a categorization task was developed in the Niv lab (the “Microbes Task”). In this task, participants see a sequence of “microbes” (Figure 1A, corners), which differ in the number and length of their spikes. On each trial, participants are asked to identify an individual microbe as belonging to a previously-identified or a new strain (cluster) of microbes, representing a previous or a new latent cause, respectively. The subjects completed 6 blocks of the task, comprising 67-75 trials total. The different blocks (not trials) had the same overall structure that is shown in Figure 1A, but we tried to make each block as distinct as possible to prevent generalization:

- We told the participants that they are seeing new microbes with completely different strains, and the three-letter strain labels were different in each block.
- The perceptual space (space of possible microbes) was actually larger than what is shown in Figure 1A, but for each block we only took a portion of it so the participants wouldn’t feel like they’ve seen those microbes before.
- The microbes in different blocks had different colors.

[2] This section contains text that is based closely on, or identical to, text found in my junior paper.

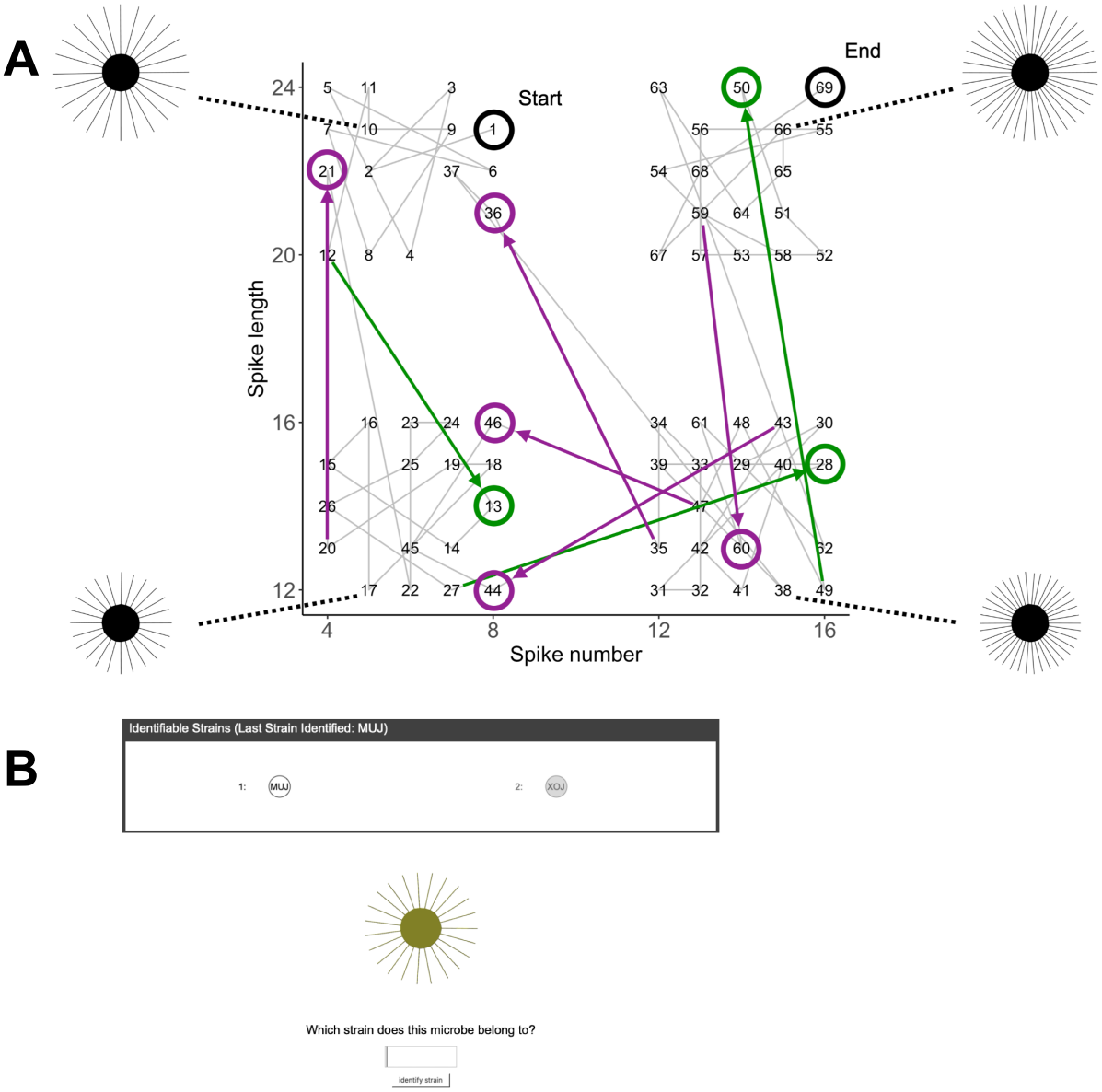

Figure 1. Representation of the Microbes Task

(A) *A sequence of microbes is presented consecutively. The numbers shown on the plot represent the trial numbers, with the lines representing two consecutive stimuli and trials. The x-axis shows the first perceptual dimension (number of spikes) and the y-axis shows the second dimension (length of spikes). The true number and length of spikes were converted into equally spaced "perceptual levels" based on a previous norming study (not described) to ensure that participants perceive the difference between two consecutive levels to be the same across the entire space. The dotted arrows connect representative microbe stimuli to the corresponding points in the perceptual space. Green arrows indicate ground-truth segmentation events (initializing a new cluster), whereas purple arrows indicate ground-truth revisit events (going back to an old cluster).* ***(B)*** *A screen capture of the Microbes Task setup as seen by the participants.*

We used the behavioral data collected from the participants' strain assignments to estimate the parameters of a computational model of the latent-cause inference process for each participant.

Schizotypy measurement

The Personality Inventory for DSM-5 (PID-5) evaluates 5 personality-trait domains: negative affect, detachment, antagonism, disinhibition, and psychoticism (Krueger et al., 2012), where the word "psychoticism" is used to refer to schizotypy. PID-5 assesses personality and related disorders, developed to be used in clinical settings to aid in diagnosis of mental health illnesses (Bach et al., 2018). In order to measure schizotypy, each participant was asked to respond to 24 items on six out of the ten PID-5 subscales (four questions per subscale): (1) "Anhedonia," (2) "Withdrawal," (3) "Suspiciousness," (4) "Unusual beliefs & experiences," (5) "Perceptual dysregulation," and (6) "Eccentricity" (for the full list of items on the questionnaire, see the Appendix). These questions were chosen because they assess schizotypal traits. Moreover, all three types of schizotypal traits – positive, negative, and cognitive – were represented. The "Anhedonia" and "Withdrawal" subscales assessed negative aspects; "Suspiciousness," "Unusual beliefs & experiences," and "Perceptual dysregulation" – positive aspects; and "Eccentricity" – cognitive aspects. The order of the items on the questionnaire was randomized.

Scoring the questionnaire

Each question was scored 0 to 3 (corresponding to "Very False," "Somewhat False," "Somewhat True," and "Very True"). Questionnaire responses were analyzed in multiple ways to yield different measures of the strength of schizotypal traits. We calculated cumulative questionnaire scores, which were obtained by summing the responses to all questions in the questionnaire (range 0 to 72). In addition, subscale scores were calculated as the sums of the responses to the questions that belonged to a subscale. For example, a subscale score for "Anhedonia" was obtained by summing the responses to questions #5, #6, #7, #8. A subscale score could range from 0 to 12.

Defining a "high schizotypy" group and a "low schizotypy" group

"High schizotypy" and "low schizotypy" groups were defined as the top and bottom 100 scorers on the self-report questions, respectively, using sum of responses as the criterion. We also performed principal component analysis (PCA) on the questionnaire data to identify the top and bottom 100 scorers along the first principal component. Using PCA and sum of responses yielded almost the same group of participants for the low and the high schizotypy groups – 96% participants identified by PCA were also identified by sum of the responses for both the high and the low schizotypy groups. As a result, below we will report results obtained by using the sum of responses only.

The latent-cause inference model

Briefly, the latent cause inference model is a Bayesian inference model with a prior over clusters and a likelihood for each cluster. The model assumes that, on each trial, the agent performs Bayesian inference in order to compute a posterior distribution over all possible latent causes. This process involves multiplying the prior probability of each latent cause given past observations by the likelihood of the current microbe given each possible latent cause (see below).

Prior probability function

Equation (1) describes the prior probability that stimulus z seen at time t belongs to latent cause k. K is the number of existing latent causes, and α is the concentration parameter that determines the propensity to start a new latent cause. In its simplest form, n_k is the observation count (how many microbes have been assigned to cause k in the past), but this can vary based on the assumption of temporal influence (see below). The prior gives the next microbe a higher prior probability to come from "strains" (causes) that have "generated" more microbes previously.

$$p(z_t = k) = \begin{cases} \frac{n_k}{\sum_{k=1}^{K} n_k + \alpha}, & k \leq K. \\ \\ \frac{\alpha}{\sum_{k=1}^{K} n_k + \alpha}, & k = K + 1. \end{cases} \quad (1)$$

Temporal decay

We assumed that the observation count n_k decays exponentially on each trial, with decay rate λ (Zhu et al., 2005) as in equation (2). Conceptually, the temporal decay is how fast a participant forgets past observations of a strain of microbes. This is rational given that the world is constantly changing, so older causal attributions might be less relevant in the present.

$$n_k = n_k * exp(-\lambda) \quad (2)$$

Likelihood function

Formula (3) represents the likelihood – the probability of observing a value $y_{d,t}$ along dimension *d* on trial *t* given cause *k*. The two dimensions *d* are the number of spikes and the length of spikes. This probability distribution takes the shape of a Gaussian distribution centered on the mean μ of the previous observations in this latent cause, and with variance of σ^2 (Kahnt, 2016), which we will refer to as the "size prior" parameter (each dimension has its own size prior). We considered each dimension to be independent, hence we computed the total likelihood by multiplying the likelihoods for each dimension.

$$p(y_{d,t}|z_t = k) = exp(\frac{-(y_{d,t} - \mu)^2}{2\sigma^2}) \quad (3)$$

In sum, the model has four independent free parameters:

- The concentration parameter α, which represents the propensity to infer a new microbe strain in the task, i.e., a new latent cause (higher α means a higher prior probability to segment the coming trial into a new strain).
- The temporal decay parameter λ, which represents how long a participant believes a latent cause is active, or the "forgetting" rate of prior observations (higher λ means faster decay).
- The size priors σ_1 and σ_2, which denote how wide or variable the latent causes that the participant infers are across each of the dimensions. In other words, these parameters indicate how much the subject is willing to generalize within a latent cause.

Model fitting

The latent-cause inference model was used to fit the Microbes Task behavioral data. Model fitting was performed to find the individual set of parameter values (α, λ, σ_1 and σ_2) that best explain the behavioral data of each subject, using code adapted from Dan-Mircea Mirea. A hierarchical fitting approach was used, which assumes that individual parameter values are sampled from a group distribution. This approach has been shown to lead to more accurate parameter estimates than non-hierarchical fitting (Katahira, 2016) as it uses group data to regularize, that is, to bring subjects whose behavior is far outside the rest of the group (outliers) more in line with the group.

Regression analysis

Multiple regression was performed to analyze the relationship between parameter values and different variables. All regression analyses controlled for age, gender, and working memory. In addition, the Benjamini-Hochberg procedure (Haynes, 2013) was

utilized to correct for multiple comparisons. The threshold of significance was set at p-values smaller than 0.05 after the Benjamini-Hochberg procedure.

Exploratory factor analysis

We performed exploratory factor analysis (EFA) using maximum likelihood estimation with varimax rotation on the subjects' responses to the questionnaire assessing schizotypal traits. The criterion for choosing the factors was to select those components that have an eigenvalue greater than 1 – this is known as the Kaiser criterion (Girden, 2001). The rationale behind the Kaiser criterion is that factors with eigenvalues less than 1 are not stable or replicable, accounting for less variability than a single variable, and thus should not be retained in the analysis (Girden, 2001).

Results

Latent causes generated by participants high in schizotypy were wider and more segmented

We hypothesized both that participants with higher schizotypy scores would initiate a greater number of clusters, which corresponds to higher segmentation of latent causes, and assign items that are different from each other to the same cluster, which represents wide latent causes. These cognitive constructs are directly related to task parameters. In our model, oversegmentation of latent causes is associated with higher concentration parameter (α) values, and wider latent causes are related to higher size prior 1 (σ_1) and/or size prior 2 (σ_2) parameter values. These relationships between parameter values and cognitive constructs were consistent with the results of simulated experiments, in which task behavior was simulated using the latent-cause inference model, taking parameter values as input (Junior Independent Work). Thus, we hypothesized that subjects with more severe schizotypal traits as determined by questionnaire score would yield higher α parameter values as well as higher σ_1 and/or σ_2 parameter values.

Multiple linear regression was performed to test if belonging to either the high schizotypy or the low schizotypy group significantly predicted parameter values after controlling for demographic variables and working memory. The results showed that belonging to the high schizotypy group significantly predicted higher α (β=0.034, SE=0.03, p=0.03) and higher σ_1 (β=0.014, SE=0.006, p=0.02) parameter values but not λ (β=-0.01, SE=0.04, p=0.75) and σ_2 (β=0.008, SE=0.006, p=0.16) parameter values (see Figure 2). Thus, the results were consistent with the hypothesis.

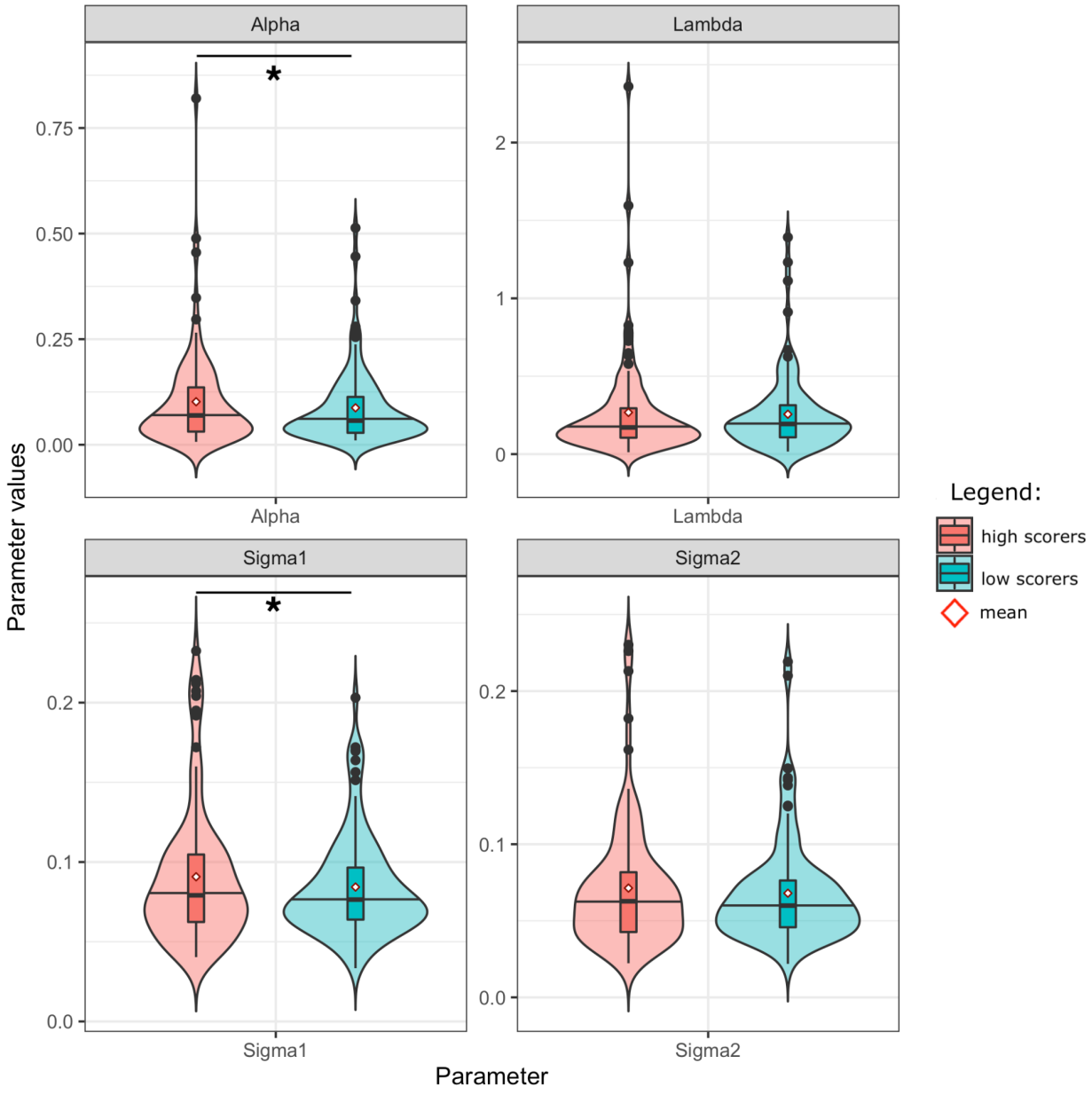

Figure 2. Parameter values of participants with high vs. low schizotypy scores (top 100 and bottom 100 scorers).
*Violin plots visualize the distribution of the four parameter values (α (Alpha), λ (Lambda), σ_1 (Sigma1), and σ_2 (Sigma2)) separately for the 100 participants with highest cumulative schizotypy scores (high scorers in pink on the left) and 100 participants with lowest cumulative schizotypy scores (low scorers in blue on the right). The black horizontal lines represent the medians; the red-outlined rhombi represent the means; and the black dots denote outliers. * denotes relationships with $p < 0.05$, corrected, which was set as the threshold for significance.*

Assessing severity of schizotypal traits as continuous rather than categorical yields different results

It is important to note that the results presented above were obtained by categorizing subjects based on cutoffs in schizotypy scores. This was done because some of the schizotypy questions had low endorsement (as expected in a general population sample), and we sought to maximize differences between post-hoc high and low schizotypy groups. However, there are benefits to using schizotypy scores of the participants as a continuous measure. One reason is that psychopathology is better described as dimensional rather than categorical since presentation of psychopathology lies on a continuous spectrum. While the categorical approach provided interesting results, we anticipated that performing analysis with dimensional measures of psychopathology would also yield valuable insights. Therefore, we also analyzed the relationship between latent-cause inference processes and schizotypal traits treating the questionnaire scores as a continuous measure and using data from all of the participants.

We used multiple linear regression to quantify the relationship between parameter values and the cumulative scores of all participants, controlling for gender, age, and working memory. It was found that the cumulative score significantly predicted σ_1 (β=3e-4, SE=1e-4, p=0.01) and σ_2 (β=3e-4, SE=1e-4, p=0.04) parameter values but did *not* significantly predict α (β=7e-4, SE=4e-4, p=0.09) and λ (β=8e-5, SE=9e-4, p=0.93) parameter values. Interestingly, these results differ from those generated by the analysis in which participants were categorized into high schizotypy and low schizotypy groups. Specifically, while both methods of analysis showed significant relationships between schizotypy and σ_1 parameter values, the categorical approach showed significant results for α but not for σ_2 while the dimensional approach showed significant results for σ_2 but not for α.

Several subscales significantly predict parameters of the latent-cause inference model

Interesting relationships could be obscured when a cumulative score is used for analysis. Therefore, we next adopted a more granular view of the relationships between specific schizotypal traits and latent-cause inference. We hypothesized that subscales assessing positive symptoms would be more likely to correlate significantly with latent-cause inference parameters than subscales assessing negative or cognitive symptoms. The subscales assessing positive symptoms include the three subscales "Suspiciousness," "Perceptual dysregulation," and "Unusual beliefs & experiences." The subscales that assess negative symptoms are "Anhedonia" and "Withdrawal," and the subscale assessing cognitive symptoms is "Eccentricity." Intuitively, positive symptoms are more directly related to aberrant latent-cause inference than negative symptoms. This intuition was explored in more detail in the introduction using "Unusual beliefs & experiences" as an example.

Multiple linear regression was used to test this hypothesis while controlling for other variables (age, gender, working memory) and adjusting the p-values to account for multiple comparisons. We found that scores on all three positive symptom subscales – "Suspiciousness," "Perceptual dysregulation," and "Unusual beliefs & experiences" – significantly predicted σ_2 parameter values ("Suspiciousness": β=0.002, SE=6e-4, p=0.02; "Perceptual dysregulation": β=0.003, SE=8e-4, p=0.02; "Unusual beliefs & experiences": β=0.002, SE=7e-4, p=0.03). In addition, "Suspiciousness" and "Unusual beliefs & experiences" subscale scores also significantly predicted σ_1 parameter values ("Suspiciousness": β=0.002, SE=6e-4, p=0.004; "Unusual beliefs & experiences": β=0.003, SE=7e-4, p=5e-5). We found that α parameter values did not correlate significantly with any of the subscale scores, which was consistent with the results of the analysis done with the cumulative score.

When linear regression analysis was performed on each question individually, the results supported the hypothesis that the "Unusual beliefs & experiences" subscale was the most related to latent-cause inference: while only one out of four questions from the

"Suspiciousness" and the "Perceptual dysregulation" subscales significantly correlated with at least one parameter value, *all four items of the "Unusual beliefs & experiences" subscale* significantly predicted at least one parameter value. Table 1 contains the statistical results for all four parameters for each questionnaire item.

Table 1. Adjusted p-values obtained by linear regression analysis of responses to questionnaire items and parameter values (after controlling for age, gender, and working memory). *P-values lower than 0.05 are highlighted in yellow.*

Subscale	Item #	α			λ			σ_1			σ_2		
		β	SE	p	β	SE	p	β	SE	p	β	SE	p
Anhedonia	5	0.007	0.005	0.4	-0.002	0.01	0.9	0.002	0.002	0.4	0.003	0.002	0.3
	6	-0.003	0.006	0.7	-0.001	0.01	0.9	5e-4	0.002	0.8	-0.001	0.002	0.7
	7	-3e-4	0.005	1	7e-4	0.01	1	0.001	0.002	0.7	-6e-4	0.002	0.8
	8	-0.003	0.005	0.7	-0.007	0.01	0.7	0.002	0.002	0.6	4e-4	0.002	0.9
Withdrawal	9	0.004	0.005	0.6	-0.008	0.01	0.6	7e-4	0.002	0.8	0.001	0.001	0.7
	10	-0.002	0.006	0.8	0.008	0.01	0.7	-5e-5	0.002	1	0.001	0.002	0.7
	11	-0.008	0.005	0.3	-0.002	0.01	0.9	-0.003	0.002	0.3	-0.002	0.002	0.4
	12	-0.003	0.005	0.7	0.003	0.01	0.8	-0.001	0.001	0.6	-3e-4	0.001	0.9
Suspiciousness	13	0.01	0.009	0.4	0.04	0.02	0.2	0.008	0.003	0.05	0.006	0.003	0.2
	14	0.007	0.005	0.4	-0.006	0.01	0.7	0.004	0.001	0.05	0.002	0.001	0.3
	15	0.02	0.006	7e-3	-0.004	0.01	0.8	0.008	0.002	1e-3	0.008	0.002	1e-3
	16	0.007	0.005	0.4	0.004	0.01	0.8	0.003	0.002	0.3	0.003	0.002	0.3
Perceptual dysregulation	17	0.01	0.008	0.3	0.01	0.02	0.7	0.006	0.003	0.1	0.01	0.003	2e-3
	18	0.005	0.009	0.7	0.03	0.02	0.3	0.004	0.003	0.3	0.004	0.003	0.3
	19	0.007	0.01	0.7	0.02	0.02	0.6	0.001	0.004	0.8	0.006	0.004	0.3
	20	0.01	0.005	0.1	-0.01	0.01	0.4	0.002	0.002	0.5	0.003	0.002	0.3
Unusual beliefs & experiences	21	0.009	0.007	0.4	0.01	0.01	0.6	0.009	0.002	1e-3	0.005	0.002	0.1
	22	0.01	0.006	0.2	0.01	0.01	0.6	0.008	0.002	4e-3	0.003	0.002	0.4
	23	0.03	0.01	0.1	0.04	0.02	0.2	0.01	0.003	4e-3	0.01	0.003	1e-3
	24	0.003	0.005	0.7	0.007	0.01	0.7	0.005	0.001	0.03	0.002	0.001	0.4
Eccentricity	37	0.003	0.005	0.7	0.004	0.01	0.8	0.002	0.002	0.3	5e-4	0.002	0.8
	38	0.01	0.005	0.2	-0.008	0.01	0.7	0.002	0.002	0.4	0.003	0.001	0.3
	39	0.01	0.005	0.06	-0.006	0.01	0.7	0.003	0.002	0.2	0.002	0.001	0.4
	40	0.01	0.005	0.2	-0.01	0.01	0.5	0.001	0.002	0.7	0.003	0.001	0.3

Exploratory factor analysis

We also performed exploratory factor analysis (EFA) on the subjects' responses to the questionnaire assessing schizotypal traits. The aim of EFA was to consider an internal structure of this set of questions and compare it to the already existing subscale

structure. Additionally, the obtained factor scores were used in a linear regression model to analyze the relationship between parameter values and these factor scores. We selected the factors that had an eigenvalue greater than one (the factors with eigenvalues above the dashed line in Figure 3). These five factors together explained 64% of the total variance.

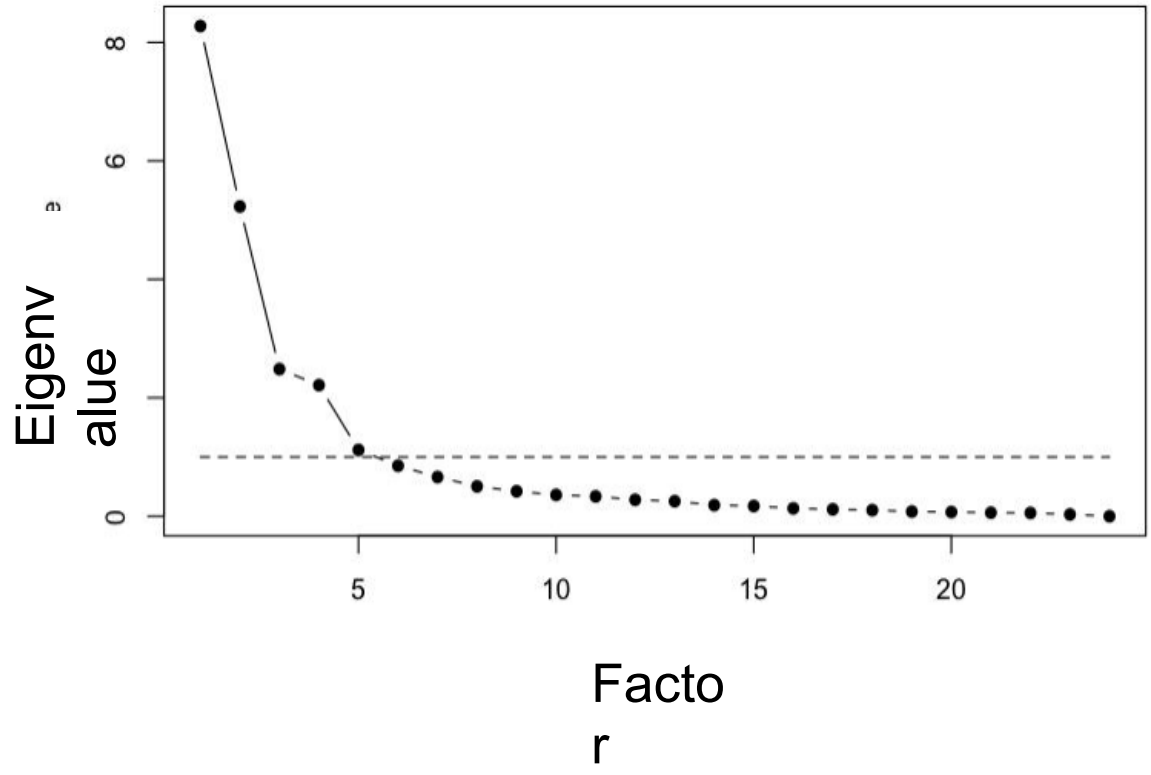

Figure 3. Scree plot.
Eigenvalues for each individual factor. The dashed horizontal line denotes the Kaiser criterion (Eigenvalue = 1). Only the factors above the Kaiser criterion were retained.

While the EFA structure (five factors) was different from the subscale organization of the questionnaire, which contained six subscales, the grouping suggested by EFA was remarkably similar to the subscale organization (see Figure 4). In fact, the only difference between the factor organization and the subscale organization was that the questions of the “Perceptual dysregulation” and “Unusual beliefs/ experiences” subscales were grouped together by EFA. Thus, the outcome of EFA was largely consistent with the subscale organization of the questionnaire.

Controlling for age, gender, and working memory and adjusting the p-values to account for multiple comparisons, the regression analysis revealed that PA2 (a factor that included the questions of the “Perceptual dysregulation” and “Unusual beliefs & experiences” subscales) significantly predicted σ_1 (β=0.007, SE=0.002, p=0.001) and σ_2 (β=0.005, SE=0.002, p=0.006) parameter values. PA5 (a factor that included the questions of the “Suspiciousness” subscale) significantly predicted α (β=0.01, SE=0.006, p=0.04), σ_1 (β=0.007, SE=0.002, p=0.001) and σ_2 (β=0.006, SE=0.002, p=0.006) parameter values. Regression analysis of factor scores yielded significant p-values for the same groups of questions as did regression analysis of subscale scores.

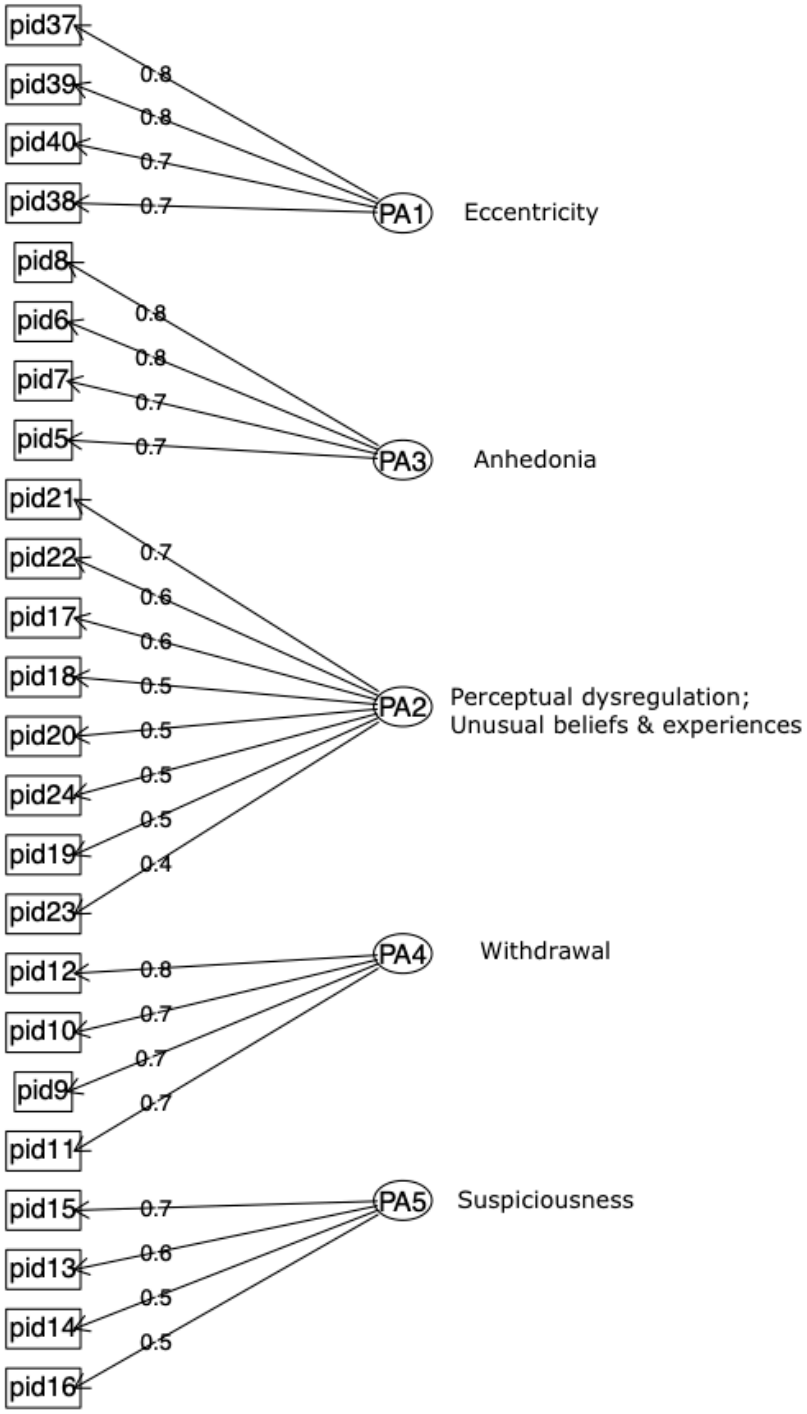

Figure 4. Question groups as suggested by EFA.
Items on the questionnaire are denoted by "pid" followed by the item number with arrows connecting factors with questionnaire items. On top of the arrows are the factor loadings of each questionnaire item. To the right of every factor are the subscales containing the questionnaire items grouped under this factor.

Supplementary results: showing the validity and reliability of the instruments

Internal consistency reliability of the questionnaire

It was important to assess the internal consistency reliability of the items within each subscale to ensure that the questions within each subscale are measuring the same construct. The internal consistency was calculated for each subscale and reported in Table 2. The alpha coefficient exceeded 0.6 for all subscales, which is described as an acceptable level in psychological/social science studies by Nunnally (1978) (as cited in Mason et al., 2005).

Table 2. Descriptive statistics (internal consistency)

Subscale	α coeff.	95% CI
Anhedonia	0.91	[0.89, 0.92]
Withdrawal	0.85	[0.82, 0.87]
Suspiciousness	0.76	[0.71, 0.80]
Perceptual dysregulation	0.64	[0.57, 0.70]
Unusual beliefs & experiences	0.70	[0.64, 0.75]
Eccentricity	0.89	[0.87, 0.91]

Split-half reliability of the Microbes Task and model fitting

We implemented a split-half approach to assess whether the parameters were stable representations of characteristics of the latent-cause inference process in an individual. In other words, we wanted to make sure that the noise (randomness) in estimating these parameters is small. To establish split-half reliability, we fit model parameters separately for the odd-numbered blocks (blocks 1, 3, and 5) and the even-numbered blocks (blocks 2, 4, and 6) of the Microbes Task for each participant. A correlation coefficient was computed for these independently-fit parameters (see Figure 5). The fact that the odd-block and the even-block parameters are highly correlated ($R > 0.65$

for all parameters, p << 0.05) shows that the Microbes Task and the model-fitting procedure are reliable instruments across the different blocks.

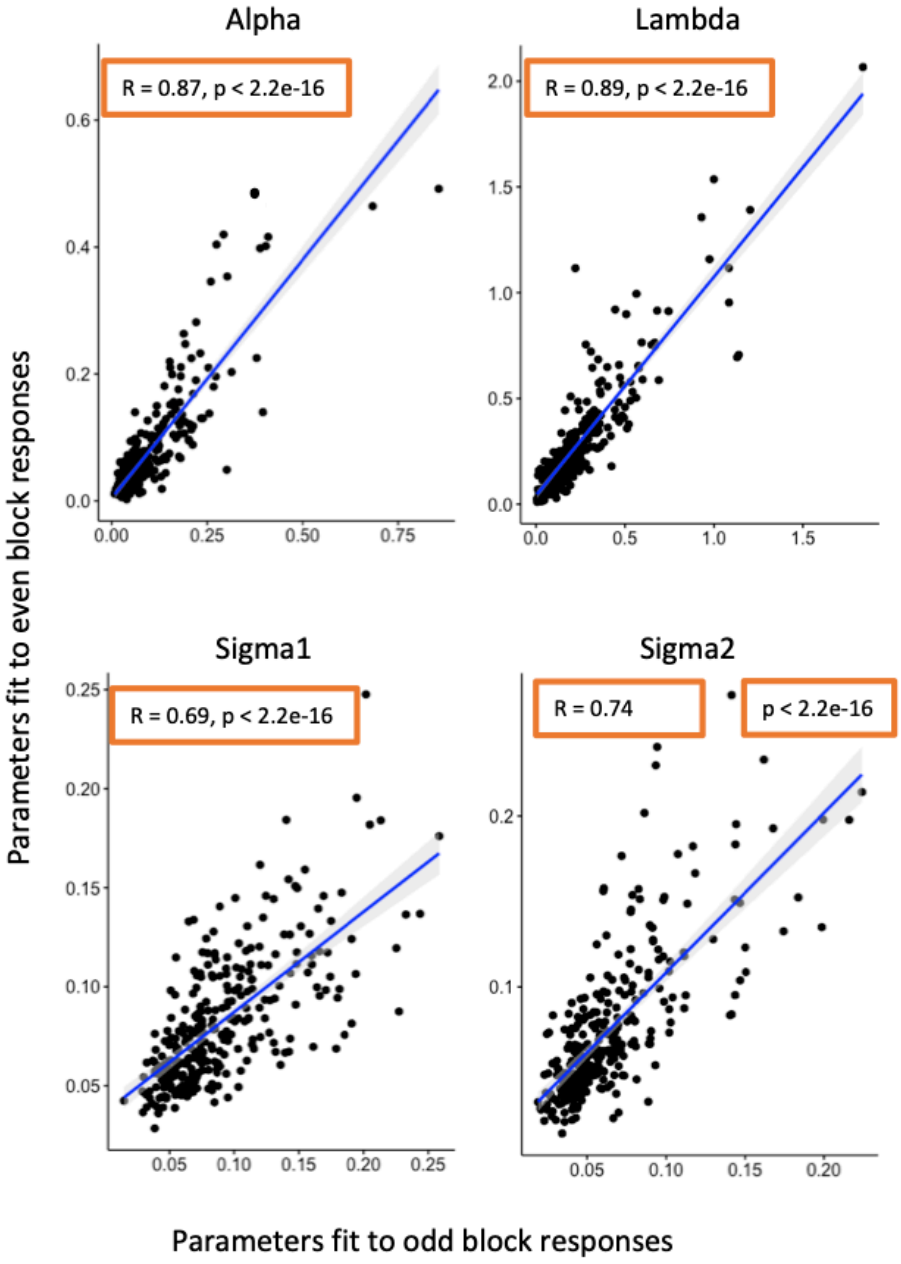

Figure 5. Correlation between parameters fit to odd block responses and parameters fit to even block responses.

Parameters fit to odd blocks (x-axis) are plotted against the parameters fit to even blocks (y-axis). The blue lines are the best fit regression lines. The gray area surrounding the blue lines represents the 95% confidence interval.

Identifiability of the model parameters

In order to ensure that the parameters can be correctly identified by the model-fitting process, we performed parameter recovery. For this, we simulated artificial data using the parameter values estimated from the subjects. Subsequently, the model was fitted to the simulated data to estimate the parameters in a case in which we know the "ground truth" parameters that generated the data. Finally, the actual and recovered parameters were correlated. The correlation coefficients were greater than 0.9 for all parameters. This also served as quality control, as low correlation coefficients would have signaled an experimental or coding error.

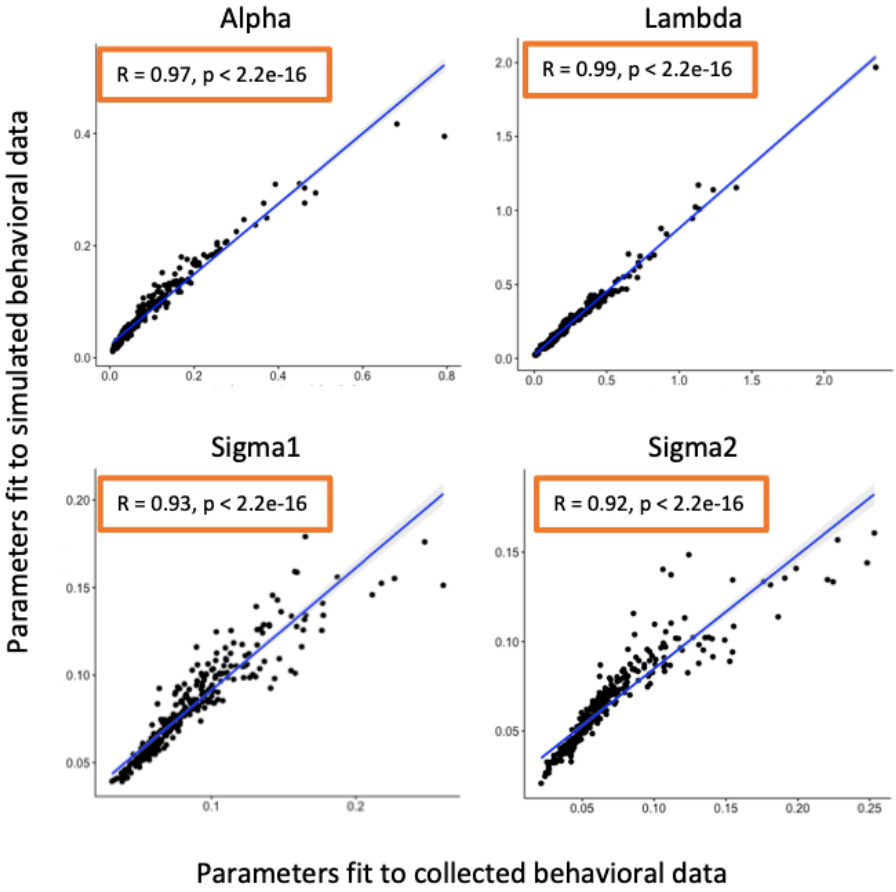

Figure 6. Correlation between parameters fit to collected behavioral data and parameters fit to simulated behavioral data.

Parameters fit to collected behavioral data (x-axis) are plotted against the parameters fit to simulated behavioral data (y-axis). The blue lines are the best fit regression lines. The gray area surrounding the blue lines represents the 95% confidence interval.

Discussion

Principal findings

Given the importance of latent-cause inference in creating a coherent interpretation of causal relationships in the world, we designed the Microbes Task: a task that allowed us to quantify the latent-cause inference process in humans. Running the Microbes Task in a large online population, we investigated the connection between latent-cause inference and schizotypy, positing that abnormal latent-cause inference could be underlying schizotypal traits. We hypothesized that higher schizotypy scores would be positively associated with more segmented and wider latent causes. The α parameter in our model operationalized how segmented are the latent causes, and the σ_1 and σ_2 parameters operationalized how wide are the latent causes. We found that when schizotypy scores were treated as a categorical variable (i.e., grouping participants with high schizotypy scores and low schizotypy groups into two groups), the hypothesis was supported in its entirety. The high schizotypy group showed significantly higher α and higher σ_1 parameter values. However, when schizotypy scores were used as a continuous variable, the schizotypy score significantly predicted only σ_1 and σ_2 but not the α parameter values. Thus, while analyzing schizotypy scores as a categorical variable suggested that people with higher schizotypy scores may be more likely to generate both more segmented and wider latent causes, treating schizotypy scores as a continuous variable was only consistent with higher schizotypy scores being associated with wider latent causes.

Given that cumulative schizotypy scores may obscure associations between latent-cause inference and specific subscales or even individual questions on the questionnaire, linear regression analyses were performed on a more granular level. Analyzing subscale scores revealed significant relationships between parameter values and all the subscales that assessed positive schizotypal traits but none of the subscales assessing cognitive nor negative schizotypal traits. To delve into even more detail, responses to each individual question were taken as regressors. Again, only the questions on the three subscales assessing positive symptoms yielded significant correlations with the parameter values.

To adopt a more data-driven approach, exploratory factor analysis (EFA) was performed to see whether there was an internal structure to the questionnaire that organized the questions better than the existing subscale organization. EFA revealed a factor structure remarkably similar to the subscale organization, with the only exception being that the questions belonging to the "Perceptual dysregulation" and "Unusual beliefs & experiences" subscales were grouped together by EFA. Regression analysis that used the factor structure yielded results that were consistent with the subscale analysis – only the questions assessing positive schizotypal traits yielded significant correlations with the parameter values.

Schizotypy scores: categorical vs. continuous

Overall, the results supported the hypothesis that schizotypy scores correlated with latent-cause inference parameters, giving credence to the idea that aberrant latent-cause inference may be a feature of schizotypy and schizophrenia-spectrum disorders. The surprising finding was that different parameter values were found to correlate significantly with schizotypy scores when the schizotypy scores were treated as a categorical or dimensional variable. While psychopathology has been traditionally described as discrete and categorical, presumably to make diagnosis more straight-forward, there has been increasing interest in using a continuous representation of psychopathology, especially in quantitative research (Krueger & Markon, 2006). When schizotypy scores were treated as a categorical variable, it was found that subjects in the high schizotypy group produced significantly higher α and σ_1 parameter values than subjects in the low schizotypy group. When schizotypy scores were treated as a continuous variable, it was found that higher schizotypy scores correlated significantly with higher σ_1 and σ_2 parameter values.

It is interesting that both procedures generated results consistent with the hypothesis that higher schizotypy scores would be correlated with generating wider latent causes (higher σ_1 and σ_2 parameter values). However, only when schizotypy scores were treated as a categorical measure did the results suggest a significant correlation between higher schizotypy scores and higher segmentation of latent causes (higher α

parameter values). It would be interesting to see whether collecting and analyzing data from more participants would eliminate this discrepancy. There may be an overrepresentation of low schizotypy scores in a larger group, affecting our ability to detect these correlations. Thus, it would be useful to intentionally include a substantial number of participants with schizotypy scores higher than a set threshold to ensure adequate representation of individuals with higher schizotypy scores in the data.

Exploratory factor analysis: grouping "Perceptual dysregulation" and "Unusual beliefs & experiences" together

EFA revealed an interesting internal organization of the questionnaire that was used in this research. Specifically, it suggested a five-factor structure that was identical to the original subscale organization of the questionnaire, except that the questions of the "Perceptual dysregulation" and "Unusual beliefs & experiences" were found to be grouped together in one factor. A search of the literature revealed at least one study that obtained a similar result. One article reported that when exploratory factor analysis was performed on more than nine subscales taken from multiple questionnaires, including DSM-5, one of the factors was the "Perceptual dysregulation" and "Unusual beliefs & experiences" subscales grouped together (Crego & Widiger, 2016).

Another study, which also performed exploratory factor analysis with DSM-5 subscales, reported a different grouping of subscales (Pires et al., 2019). Specifically, "Unusual beliefs & experiences" and "Perceptual dysregulation" were sorted into different factors. "Unusual beliefs & experiences" was grouped with "Suspiciousness" and "Rigid perfectionism" (this subscale was not included in the research described by this paper) while "Perceptual dysregulation" was grouped with "Eccentricity." However, it was interesting that "Perceptual dysregulation" and "Eccentricity" were both found to load secondarily (>0.3 loadings) onto the factor containing "Unusual beliefs & experiences" (Pires et al., 2019).

Grouping of "Unusual beliefs & experiences" and "Perceptual dysregulation" together makes sense intuitively as both subscales assess the psychotic dispositions of the

subjects. However, the fact that the study by Pires et al. (2019) yielded a factor structure that does not group these two subscales together suggests that the outcome of performing EFA on these DSM-5 subscales is not universal. Moreover, it lends credence to including both subscales in studies of schizotypy as they are not measuring strictly the same construct. Nevertheless, the results of the EFA performed in this study supports the idea that there may be some overarching construct that unites “Unusual beliefs & experiences” and “Perceptual dysregulation.” The most likely candidate for this construct is psychosis-proneness.

Advantages of using the Microbes Task over other tasks to study latent-cause inference

There is an ever-present challenge in the field of computational neuropsychiatry research to develop behavioral tasks that are highly reliable and to use computational models that are identifiable and capture meaningful aspects of the task behavior. Many cognitive and behavioral tasks commonly used in research suffer from poor reliability (Enkavi et al., 2019; Hedge et al., 2018). In this context, our assessment of the Microbes Task as a psychometric tool is largely favorable. With the alpha coefficients exceeding 0.6 for all subscales, it has high internal consistency. In addition, split-half reliability test suggested a relatively high identifiability of the Microbes Task.

Moreover, our newly developed Microbes Task compares favorably with other behavioral tasks that were used to assess categorization abilities of people with schizotypy or schizophrenia-spectrum disorders. One such test was a word association task, in which participants were asked to choose one out of four words that most closely related in meaning to a target word (Morgan et al., 2009). Another study reported using the Category Generation Test (CGT), which involves sorting pictures of objects from five taxonomic groups, for example, animals (Doughty et al., 2009). Comparing the Microbes Task with the word association test, the Microbes Task has the advantage of being independent of language processing. Unlike CGT, the Microbes Task uses artificially created stimuli, which minimizes the possibility of interaction effects arising from previous exposure to the objects categorized during the task. Another important

advantage that the Microbes Task has above both tests is that the categories are not specified, and the participant is able to create as many clusters as there are “microbes” presented. This allows greater flexibility during performance, making it possible to capture a greater range of behaviors, especially the extremes of the range. All of these factors contribute to the overall suitability of the Microbes Task as a behavioral individual-differences measure. Moreover, these advantages of the Microbes Task make a compelling case for the addition of this task to the repertoire of methodologies in computational psychiatry.

Limitations

This study has several limitations. First, while using self-report questionnaires to assess schizotypal traits provided many benefits to the study (e.g., it made it possible to collect data from participants online, not being restricted to a subject pool geographically), these measures could also have introduced sources of uncertainty. There is inherent heterogeneity in how participants respond to self-report questionnaire items (Salters-Pedneault & Rice, 2020). Some subjects may have a higher propensity to be influenced by the social desirability bias, leading this subset of participants to respond differently to the questionnaire items than other participants. Another source of response bias is heterogeneity in participants’ introspective ability and interpretation of the questionnaire items. Some participants may be more attentive to their experiences, making them more likely to endorse the questionnaire items. In our experiment, we did take measures to minimize some common sources of bias, for instance, randomizing the order of the questionnaire items to reduce question-order bias.

One interesting idea that was not explored in this study is the possibility of aberrant latent-cause inference processes influencing how a participant responds to the questionnaire assessing schizotypal traits. It is possible that a particular subset of participants who tended to behave in a certain way during the behavioral task could also have tended to answer the questionnaire in a systematically different way than other participants, without actually having specific psychopathological traits. For example, if an individual has a propensity to attribute events to over-generalized (wider) latent

causes, that individual may be more likely to endorse more questionnaire items if that person can convince themselves that a certain questionnaire item is relevant to an experience they have had, while an average individual may be less likely to make the connection between that questionnaire item and the same experience. The data obtained from the over-generalizing participant would be consistent with a positive correlation between schizotypy score and σ_1/σ_2 parameter values. However, this subject may not necessarily exhibit higher than normal schizotypal traits, despite yielding a higher schizotypy score on the questionnaire. This limitation could be potentially mitigated by administering additional schizotypy-assessing questionnaires with binary response options, making it less likely that even an over-generalizing participant would endorse a description that does not apply to them.

Future directions

The results of this research are exciting as they suggest that aberrant latent-cause inference processes may indeed play a role in certain schizotypal traits. It would be fruitful to conduct additional studies to explore the relationship between latent-cause inference and schizotypal traits. While the research described in this paper was performed with subjects who lie on the neurotypical diversity spectrum, it would be interesting to continue this research with subjects with schizophrenia. More robust results would be expected from this participant pool as latent-cause inference processes would be more likely to deviate strongly from the neurotypical range. However, it is important to note that working with a clinical population presents its own difficulties, since individuals in the clinical population can be in an active psychosis state or medicated, which could unpredictably affect their performance on the behavioral task. Another interesting future direction is working on developing the Microbes Task as an evaluative tool for schizotypal traits and even an objective assessment tool for schizophrenia-spectrum disorders. Finally, a better understanding of the role of deviations in the latent-cause inference theory in schizophrenia-spectrum disorders could be used to develop innovative psychotherapy approaches. This idea has exciting clinical implications. Schizophrenia is notoriously hard to treat, but maybe developing psychotherapy that targets latent-cause inference could be the breakthrough the

medical field needs to obtain better outcomes in schizophrenia treatment. In conclusion, this research has compelling implications for future studies of the role of latent-cause inference in schizotypy and schizophrenia-spectrum disorders.

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Appendix

Subjects were asked to fill out a self-report questionnaire to assess their schizotypal traits. 40 of the 42 questions included in the questionnaire comprise a subset of questions from the the Personality Inventory for DSM-5 (PID-5). The order of the questions was randomized for each subject. Participants were asked to select one of four answer options – “Very False,” “Somewhat False,” “Somewhat True,” “Very True” – to self-report how well they believed the question/statement described them.

The remaining two questions were “infrequency items” written by graduate student Dan-Mircea Mirea, designed to filter out the responses of the subjects who may not have been paying attention. The two infrequency items (included in the table below, were designed in a way that most participants, regardless of schizotypal traits, would answer the question in a similar way. The two infrequency items were expected to be answered oppositely to filter out those participants who chose the same answer option for every question regardless of the content. The portion of participants, who failed to respond in an expected manner, was less than 10%. Data obtained from these subjects were not used in the analysis.

Subscale/ infrequency item	Question #	Question
Anhedonia	5	Nothing seems to interest me very much.
	6	I almost never enjoy life.
	7	I almost never feel happy about my day-to-day activities.
	8	Nothing seems to make

		me feel good.
Withdrawal	9	I keep my distance from people.
	10	I don’t like spending time with others.
	11	I’m not interested in making friends.
	12	I avoid social events.
Suspiciousness	13	Plenty of people are out to get me.
	14	I’m always on my guard for someone trying to trick or harm me.
	15	I suspect that even my so-called "friends" betray me a lot.
	16	It seems like I'm always getting a "raw deal" from others.
Perceptual dysregulation	17	It's weird, but sometimes ordinary objects seem to be a different shape than usual.
	18	Sometimes I feel "controlled" by thoughts

		that belong to someone else.
	19	Sometimes I think someone else is removing thoughts from my head.
	20	Things around me often feel unreal, or more real than usual.
Unusual beliefs & experiences	21	I often have unusual experiences, such as sensing the presence of someone who isn't actually there.
	22	I have seen things that weren't really there.
	23	Sometimes I can influence other people just by sending my thoughts to them.
	24	I've had some really weird experiences that are very difficult to explain.
Eccentricity	37	People have told me that I think about things in a really strange way.
	38	Others seem to think I'm

		quite odd or unusual.
	39	I think about things in odd ways that don't make sense to most people.
	40	I often have thoughts that make sense to me but that other people say are strange.
Infrequency items (II)	II1	Sometimes I can lift a car with my bare hands.
	II2	I never worry about the all the bad things the ancient filonians did.

The expected response to II1 was “Very False” and to II2 was “Very True.”