

Apophenia as the Disposition to False Positives: A Unifying Framework for Openness and Psychoticism

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Positive symptoms of schizophrenia and its extended phenotype—often termed psychoticism or positive schizotypy—are characterized by the inclusion of novel, erroneous mental contents. One promising framework for explaining positive symptoms involves apophenia, conceptualized here as a disposition toward false-positive errors. Apophenia and positive symptoms have shown relations to openness to experience (more specifically, to the openness aspect of the broader openness/intellect domain), and all of these constructs involve tendencies toward pattern seeking. Nonetheless, few studies have investigated the relations between psychoticism and non-self-report indicators of apophenia, let alone the role of normal personality variation. The current research used structural equation models to test associations between psychoticism, openness, intelligence, and non-self-report indicators of apophenia comprising false-positive error rates on a variety of computerized tasks. In Sample 1, 1,193 participants completed digit identification, theory of mind, and emotion recognition tasks. In Sample 2, 195 participants completed auditory signal detection and semantic word association tasks. Psychoticism and the openness aspect were positively correlated. Self-reported psychoticism, openness, and their shared variance were positively associated with apophenia, as indexed by false-positive error rates, whether or not intelligence was controlled for. Apophenia was not associated with other personality traits, and openness and psychoticism were not associated with false-negative errors. Findings provide insights into the measurement of apophenia and its relation to personality and psychopathology. Apophenia and pattern seeking may be promising constructs for unifying the openness aspect of personality with the psychosis spectrum and for providing an explanation of positive symptoms. Results are discussed in the context of possible adaptive characteristics of apophenia as well as potential risk factors for the development of psychotic disorders.

General Scientific Summary

Our research using two samples taken from the general population suggests that the personality aspect of openness (individual differences in creativity and imagination, representing half of a broader openness/intellect trait) and symptoms of the psychosis spectrum are related to each other and may share underlying mechanisms. In the current work, we provide novel evidence that apophenia—the tendency to observe meaningful patterns where there are none present—may be an important cognitive mechanism at the core of what is shared between openness and risk for psychosis.

Keywords: schizotypy, openness to experience, false positives, schizophrenia, intelligence

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Psychosis refers to a loss of contact with reality that is present in various forms of psychopathology, most prominently schizophrenia. Symptoms of schizophrenia involve maladaptive alterations in affect, cognition, and behavior and are typically separated into negative, disorganized, and positive symptoms. Negative symptoms include constricted affect, anhedonia, and social withdrawal. Disorganized symptoms consist of disrupted thought processes that can produce incoherent or bizarre speech and behavior. Positive symptoms—hallucinations and delusions—are perhaps the most recognizable and defining feature of psychotic disorders, described as positive because they involve the addition of novel and erroneous mental content. One construct that may be useful for understanding positive symptoms across psychotic disorders is apophenia.

The term apophenia was coined by Klaus Conrad to describe a core feature of psychosis: the perception of meaningful patterns where none, in fact, exist (Mishara, 2010). In our current conceptualization, apophenia can be seen as synonymous with a disposition toward type I errors (false positives) in both perception (as in hallucinations) and belief (as in delusions). This conceptualization of apophenia is in line with the concept of aberrant salience—the inappropriate assignment of attention or meaning to external objects and internal representations—a proposed mechanism of psychosis that fits well into broader theoretical frameworks involving the function of dopamine in salience and pattern detection (Kapur, 2003). Apophenia may involve the assignment of unwarranted salience to information in one's environment, thus leading to an increase in false-positive errors. These tendencies may remain relatively widespread throughout the population because in healthy functioning, things perceived as salient are likely to involve real and meaningful patterns.

Given that hallucinations and delusions can both be seen as severe instances of type I errors, it is not surprising that individuals with schizophrenia show high rates of such errors in behavioral tasks (Blakemore, Sarfati, Bazin, & Decety, 2003). Apophenia is not limited to those with severe psychopathology, though, and it also occurs regularly throughout the general population. Apophenia, as understood today, can include any instance in which a pattern is falsely detected or labeled as meaningful when it is actually absent or attributable to chance. Everyday examples could include believing your name was called when hearing random sounds, seeing animals in the clouds, and believing in concepts such as astrology or good-luck charms. Importantly, apophenia may be the result of heightened pattern seeking, which leads to increased rates of false-positive errors, as a tradeoff for decreased false-negative (type II) errors. However, high levels of pattern seeking are not identical to apophenia. The result of a sensitive pattern detection system can be either adaptive (e.g., innovative) or maladaptive (e.g., departing from reality), but if it is to be adaptive, it must be accompanied by the capacity to distinguish between true and false patterns among those detected (DeYoung, Grazioplene, & Peterson, 2012).

The majority of existing research on apophenia has operationalized the construct using self-report measures assessing positive symptoms of schizophrenia and its extended phenotype—schizotypy. Individual differences in schizotypy are conceptualized as variation in traits that are continuously distributed and correspond to the positive, negative, and disorganized symptoms of schizophrenia (Kwapil & Barrantes-Vidal, 2014). Positive schizotypy,

also known as psychoticism, is associated with ideas of reference, magical thinking, and unusual perceptual experiences—milder versions of delusions and hallucinations (Krueger, Derringer, Markon, Watson, & Skodol, 2012). This construct should not be confused with Eysenck's psychoticism, a misleadingly named trait reflecting impulsive nonconformity, low agreeableness, and low conscientiousness but not psychosis proneness (Knezevic et al., 2019). Advantages of studying psychoticism in the general population include (a) fewer confounds stemming from use of psychoactive medications, comorbidity, and functional impairment; (b) greater capacity to participate in research; and (c) a broader range of the variables of interest. Although previous attempts to measure and characterize apophenia have largely focused on self-report measures designed to assess psychoticism and related traits (e.g., DeYoung et al., 2012), a handful of studies have also attempted to measure apophenia with behavioral tasks (Brugger & Graves, 1997; Chen, Hsiao, Hsiao, & Hwu, 1998; Fyfe, Williams, Mason, & Pickup, 2008; Galdos et al., 2011; Grant, Balser, Munk, Linder, & Hennig, 2014; Mohr, Graves, Gianotti, Pizzagalli, & Brugger, 2001).

Although existing research on the non-self-report assessment of apophenia is somewhat sparse, we now provide an overview. Brugger and Graves (1997) assessed apophenia using a task in which participants are asked to complete a short puzzle game with reinforcement based on participants' response time; after the puzzle task, participants are asked whether other aspects of their behavior (which did not, in reality, influence reinforcement frequency) were related to reinforcement frequency. Another task used to assess apophenia is a theory of mind test in which simple geometric shapes move in ways that are either social or random in nature (in the social condition, the shapes move like interacting agents, and most people can clearly recognize behaviors such as help seeking, encouragement, fear, etc.); participants are asked to label the motion in each trial as either social or random (Fyfe et al., 2008). Galdos et al. (2011) used an auditory signal detection task in which participants listen to white noise and speech masked with white noise and are asked to indicate whether or not speech was present. Grant et al. (2014) used a word detection task in which participants are asked to state whether words or nonwords were present inside 15 letter strings. Finally, word association tasks are used to assess apophenia by asking participants whether or not a series of word pairs or groups are semantically related (Mohr et al., 2001). Across the aforementioned tasks and studies, false-positive errors and erroneous associations were positively associated with psychoticism.

A major weakness for many of these studies has been use of only a single task at a time to assess apophenia. False positives on any given task may be influenced by aspects of task-specific performance that are irrelevant to a general tendency toward apophenia. In the present study, therefore, we use multiple tasks and a latent variable approach to assess the general tendency toward false-positive errors. Furthermore, the current research uses two large community samples with a total of 1,388 participants, an obvious improvement over the majority of previous studies on this topic, which have typically used single samples with fewer than 100 participants (e.g., Brugger & Graves, 1997; Fyfe et al., 2008; Mohr et al., 2001).

Although apophenia has been primarily studied in relation to psychoticism, elements of normal personality may also play a role.

Efforts are increasingly being made to integrate models of normal personality and psychopathology because of the recognition that the major dimensions of risk for psychopathology correspond fairly closely to dimensions of normal personality (DeYoung & Krueger, 2018; Kotov et al., 2017). The Five-Factor Model or Big Five is well established as a description of the major dimensions of normal personality variation, and four of its dimensions (neuroticism, extraversion, agreeableness, and conscientiousness) clearly correspond to major dimensions of psychopathology (negative affect or internalizing, detachment, antagonism, and disinhibition, respectively). Psychoticism has been the dimension of psychopathology most difficult to integrate with normal personality models because it often does not seem to correspond well with the openness/intellect dimension of the Big Five, despite theoretical expectations that psychoticism resembles maladaptive openness and occasional empirical associations consistent with those expectations (De Fruyt et al., 2013; Lo et al., 2017; Piedmont, Sherman, Sherman, Dy-Liacco, & Williams, 2009; Suzuki, Samuel, Pahlen, & Krueger, 2015).

Recent empirical developments have clarified the source of this difficulty. Despite its frequent use as the label for one of the Big Five dimensions, openness to experience is actually just one of two major subfactors or aspects of the broader openness/intellect dimension, with the other being intellect (DeYoung, Quilty, & Peterson, 2007; DeYoung, Quilty, Peterson, & Gray, 2014). The openness aspect encompasses fantasy-proneness and aesthetic interests, whereas intellect reflects intellectual confidence and intellectual engagement. (When we use the term openness by itself, we are referring to the subfactor, never the broader openness/intellect dimension.) Although apophenia and psychoticism are typically at least weakly negatively associated with IQ and intellect, they are positively associated with openness and can be conceived as maladaptive variants of this personality trait, forms of openness to implausible patterns (Chmielewski, Bagby, Markon, Ring, & Ryder, 2014; DeYoung et al., 2012, 2016; Wiggins & Pincus, 1989). A number of studies show that psychoticism and openness share variance, although often less than the other Big Five traits and their psychopathological variants, at least in part because their association is suppressed by their opposite associations with intellect and IQ (DeYoung et al., 2012, 2016; Chmielewski et al., 2014). Furthermore, although psychoticism, like almost all forms of psychopathology, has a sizable association with neuroticism, it loads primarily on a factor with openness, not neuroticism, when intellect and openness are measured separately (De Fruyt et al., 2013; DeYoung et al., 2012, 2016). Additionally, evidence suggests at least partially overlapping biological correlates of openness and psychoticism (Blain, Grazioplene, Ma, & DeYoung, 2019; Grazioplene, Chavez, Rustichini, & DeYoung, 2016; Jung, Grazioplene, Caprihan, Chavez, & Haier, 2010; Smeland et al., 2017; Wright, Pahlen, & Krueger, 2017). Finally, another possible confound in clearly establishing a relation between psychoticism and openness is failure to separate positive and negative schizotypy dimensions because negative schizotypy is negatively related to openness (Chmielewski et al., 2014; Ross, Lutz, & Bailley, 2002). The present research seeks to clarify the relation between openness and psychoticism by examining their association with non-self-report measures of apophenia.

When studying the role of apophenia in psychoticism and openness, it is important to consider more general cognitive deficits as well. Low intelligence is a common risk factor for most forms of

psychopathology and may confer particular vulnerability to schizophrenia (Khandaker, Barnett, White, & Jones, 2011; Zammit et al., 2004). Moreover, individuals with psychosis show specific deficits in social cognition and working memory (Mier & Kirsch, 2015; Park & Holzman, 1992), and psychoticism is also negatively correlated with performance in these domains (Blain, Peterman, & Park, 2017; Park & McTigue, 1997). Pertinent to the current study, intelligence is positively associated with stimulus discrimination (Melnick, Harrison, Park, Bennetto, & Tadin, 2013) and inversely associated with tendencies toward type I errors (Tomprowski & Simpson, 1990). Research and theory suggest that intelligence may moderate the association between apophenia and dysfunction (DeYoung et al., 2012; Grant et al., 2014). Therefore, when examining associations between psychoticism and apophenia, it is important to control for covariance explained by general cognitive ability. Few studies have examined the relation between psychoticism and non-self-report indices of apophenia in large community samples, and even fewer have considered the possible explanatory roles of intelligence and openness.

The current research sought to overcome these limitations and also incorporate a multiindicator design that assessed apophenia using a variety of computerized tasks, representing a range of perceptual and cognitive domains. As noted above, behavior in any given task is influenced by a number of task-specific factors, such that measuring a construct reliably using tasks and avoiding underestimation of true effect sizes typically requires multiple tasks. Indeed, research suggests that the psychometric quality of individual behavioral tasks is often deficient and that using multiindicator designs in a latent variable modeling framework can correct many such deficiencies (Campbell & Fiske, 1959; Nosek & Smyth, 2007). This is likely to be especially important when assessing the tendency toward broad classes of error, across diverse tasks, because errors on any single task should be influenced by specific abilities and reactions to that particular task as well as by the general tendency toward a given type of error (in this case type I errors).

Because psychoticism, openness, and apophenia all involve tendencies toward pattern seeking and perceptual sensitivity, they can be expected to share at least a moderate amount of variance. In the current research, we attempted to clarify relations among these constructs. Specifically, we investigated the relations among self-report measures of psychoticism, openness, and apophenia as indexed by false-positive errors across a range of behavioral tasks that require participants to draw connections or detect patterns. We hypothesized that latent factors corresponding to psychoticism and openness would be positively correlated and that psychoticism, openness, and a latent factor accounting for their shared variance would be associated positively with participants' disposition toward false-positive responses. Finally, we anticipated these patterns of association would be specific to false-positive errors, rather than also generalizing to variance shared with or specific to false negative errors.

Method

Participants

Sample 1 included 1,193 participants (656 females) from the Human Connectome Project. The sample included individuals between the ages of 22 and 37 years ($M = 28.8$, $SD = 3.7$). Exclusion criteria included a history of severe psychiatric, neuro-

logical, or medical disorders. Participants were not excluded for mild to moderate psychopathology (i.e., psychopathology that did not result in hospitalization or treatment over a period of greater than 1 year). Thus, given population estimates, approximately 15–20% of the sample would likely warrant a Diagnostic and Statistical Manual of Mental Disorders, fifth edition (*DSM-5*) diagnosis (National Institute of Mental Health, 2017).

Sample 2 included 195 undergraduate participants (119 females) between the ages of 18 and 44 years ($M = 21.1$, $SD = 4.8$) recruited on the University of Minnesota Twin Cities campus. They were not screened or excluded for psychiatric illness.

Self-Report Measures

Sample 1.

NEO Five-Factor Inventory (NEO-FFI; Costa & McCrea, 1992). The NEO-FFI is a measure of the Big Five personality traits. It consists of 60 items taken from the longer NEO Personality Inventory, Revised (NEO PI-R; Costa et al., 1992) and uses a 5-point Likert scale. The NEO-FFI does not include subscales for openness and intellect within the broader openness/intellect factor; thus, to create an openness aspect scale, correlations of items from the full NEO-FFI openness scale were examined in relation to openness and intellect scales from the Big Five Aspect Scales (BFAS; DeYoung et al., 2012). Previous work has been done to extract a similar openness aspect scale designed using the full NEO PI-R, based on item-associations with the BFAS in three independent samples (Ross & DeYoung, 2018); this latter scale

has been used in previous research examining relations of openness and intellect with psychoticism (Suzuki, Griffin, & Samuel, 2017). Items from this NEO PI-R openness scale that are also included in the NEO-FFI were selected to create an FFI openness scale for use in the current research. These included “I don’t like to waste my time daydreaming (reverse coded),” “I am intrigued by the patterns I find in art and nature,” “Poetry has little or no effect on me (reverse coded),” and “Sometimes when I am reading poetry or looking at a work of art, I feel a chill or wave of excitement.”

For the current study, additional validation was conducted using the Eugene Springfield Community Sample (described in our online supplementary materials). Based on item correlations in that sample, all items included in our FFI openness scale had a correlation with BFAS openness of .30 or greater and this correlation with openness was at least .15 greater than the correlation with intellect. Furthermore, there was a very strong positive correlation (approaching unity) between latent variables indicated by the four items of the FFI openness aspect scale and BFAS openness items, $r = 1.0$, $p < .001$, whereas the latent correlation between the FFI openness aspect scale and BFAS Intellect, $r = .41$, $p = < .001$ was significantly smaller ($z = 47.1$, $p < .001$). Nonetheless, to assuage concerns regarding use of an ad hoc shortened scale, we also repeated all analyses with the full NEO-FFI openness scale, which yielded results substantively identical to our main findings, likely because of the higher degree of representation of openness compared with intellect in the FFI. As per the suggestion of a

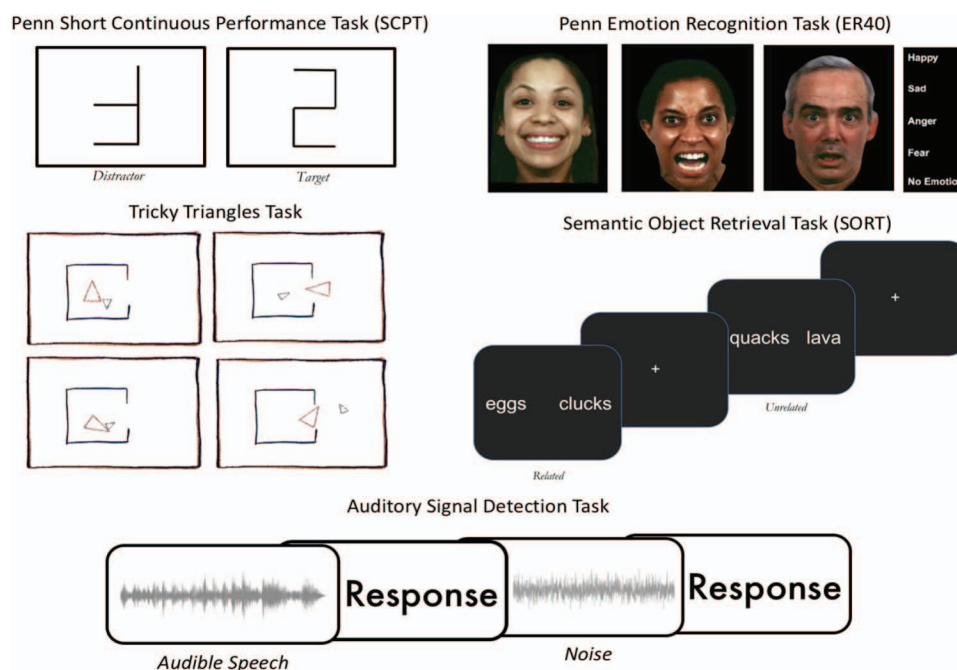


Figure 1. Behavioral apophenia tasks. Images of faces were taken from the ER40 task from the research database <https://www.med.upenn.edu/bbl/2dfaces.html>, which includes publicly available research images described in “A method for obtaining 3-dimensional facial expressions and its standardization for use in neurocognitive studies,” by R.C. Gur, R. Sara, M. Hagendoorn, O. Marom, P. Hughett, L. Macy, T. Turner, R. Bajcsy, A. Posner, and R.E. Gur, 2002, *Journal of Neuroscience Methods*, 115, pp. 137–143. See the online article for the color version of this figure.

reviewer, neuroticism and conscientiousness items from the FFI were used in discriminant validity analyses.

Achenbach Self-Report (ASR; Achenbach, 2009). Participants were administered the ASR, an instrument used to assess psychopathology. Each item uses a three-point Likert scale. In the current study, only psychoticism items were used, as the broader thought problems scale from which they were taken includes items related to obsessiveness and self-injury. Items included “I hear sounds or voices that other people think aren’t there,” “I see things that other people think aren’t there,” “I do things that other people think are strange,” and “I have thoughts that other people would think are strange.”

Sample 2.

Big Five Aspect Scales (DeYoung et al., 2007). The BFAS consists of 100 items that use a 5-point Likert scale. The questionnaire is based on the Five-Factor Model and breaks down each of the factors into two aspects. In the current study, the openness aspect scale was used. For latent variable modeling, items were broken into four parcels, using the first four items to create two parcels of two items each and the remaining six items to create two parcels of three items each. The neuroticism and conscientiousness items from the BFAS were used in discriminant validity analyses.

Multidimensional Personality Questionnaire (MPQ; Tellegen & Waller, 2008). Participants completed 34 MPQ items that form the absorption subscale. The full name of the construct measured is openness to absorbing and self-altering experiences (Tellegen & Atkinson, 1974), which is a good representation of the

shared variance of openness and psychoticism (DeYoung, Carey, Krueger, & Ross, 2016). Each item used a 5-point Likert scale.

Personality Inventory for the DSM-5 (PID-5; Krueger et al., 2012). The PID-5 is a questionnaire that includes 220 items rated on a 4-point Likert scale. This inventory is used to assess symptoms of personality disorder in the alternative model from Section III of *DSM-5*. The PID-5 includes 25 facet scales that reflect five higher-order dimensions: negative affect, detachment, psychoticism, antagonism, and disinhibition. For the current study, the eccentricity, perceptual dysregulation, and unusual beliefs and experiences facet scales (from the broader psychoticism domain) were used.

Short Oxford-Liverpool Inventory of Feelings and Experiences (Mason, Linney, & Claridge, 2005). This inventory is a multidimensional measure that assesses positive, negative, and disorganized schizotypy as well as nonconformity. Each item uses a true or false response. In the current study, we used only a sum score for the unusual experiences subscale.

Intelligence Measures

Sample 1. Intelligence was assessed using the National Institutes of Health Toolbox Picture Vocabulary and List Sorting tests as well as the Penn Matrix Test. In the Picture Vocabulary test, participants selected which picture from a selection set most closely matched the meaning of a presented word. For the List Sorting test, participants were required to remember and sort a list

Table 1
Descriptive Statistics

Variables	<i>M</i> (<i>SD</i>)	Skewness	[Minimum, maximum]
Sample 1			
Openness	2.2 (0.8)	0.1	[0, 4]
Psychoticism	0.4 (0.9)	2.5	[0, 6]
ToM false positives (%)	8.5 (10.0)	4.6	[0, 100]
SPCPT false positives	28 (5.5)	1.5	[0, 28]
Emotion false positives	0.9 (1.3)	2.0	[0, 8]
ToM false negatives (%)	2.7 (8.3)	3.5	[0, 60]
SPCPT false negatives	3.6 (2.3)	0.9	[0, 15]
Emotion false negatives	3.6 (2.3)	0.9	[0, 15]
Matrix test accuracy	16.7 (4.9)	−0.6	[4, 24]
Picture vocabulary	116.6 (9.9)	0.1	[90.7, 153.1]
List sorting	110.9 (11.3)	0.2	[80.8, 144.5]
Sample 2			
PID-5 eccentricity	1.1 (0.7)	0.2	[0, 3]
PID-5 unusual beliefs	0.7 (0.6)	0.7	[0, 2.3]
PID-5 perceptual	0.7 (0.5)	0.6	[0, 2.3]
O-LIFE positive	9.2 (2.4)	−0.9	[0, 12]
MPQ absorption	37.7 (18.8)	0.3	[4, 92]
BFAS openness	3.5 (0.5)	0.2	[2.1, 5]
Semantic false positives	5.7 (4.6)	1.9	[0, 29]
Auditory false positives	0.9 (1.9)	3.6	[0, 12]
Semantic false negatives	9.0 (5.0)	1.1	[0, 30]
Auditory false negatives	11.9 (7.3)	1.9	[0, 57]
WAIS vocabulary scaled	12.3 (2.4)	−0.3	[2, 19]
WAIS similarities scaled	11.9 (2.4)	−0.1	[6, 18]
WAIS matrix scaled	10.7 (2.6)	−0.2	[3, 18]
WAIS block design scaled	11.3 (3.1)	0.0	[4, 19]

Note. ToM = theory of mind task; SPCPT = short Penn continuous performance task; PID-5 = Personality Inventory for the *DSM-5*; O-LIFE = Oxford-Liverpool Inventory of Feelings and Experiences; WAIS-IV = Wechsler Adult Intelligence Scale, fourth edition; MPQ = Multidimensional Personality Questionnaire; BFAS = Big Five Aspect Scales.

Table 2
Pearson Correlations Among Sample 1 Measures

Variables	O-1	O-2	O-3	O-4	P-1	P-2	P-3	P-4	PMAT	Vocab	List	ToM FP	SPCPT FP	Emo FP	ToM FN	SPCPT FN	Emo FN
O-1	1.0																
O-2	.18	1.0															
O-3	.14	.40	1.0														
O-4	.12	.49	.67	1.0													
P-1	.02	.05	.06	.07	1.0												
P-2	.02	.02	.06	.07	.48	1.0											
P-3	.08	.11	.12	.16	.18	.15	1.0										
P-4	.12	.15	.12	.16	.16	.18	.61	1.0									
PMAT	.14	.13	-.02	.01	-.04	-.07	-.01	.05	1.0								
Vocab	.23	.19	.02	.04	-.08	-.10	-.05	.02	.47	1.0							
List	.11	.10	-.04	-.03	.00	-.05	-.04	.02	.37	.34	1.0						
ToM FP	-.01	.01	.07	.06	.14	.08	.07	.08	-.09	-.10	-.06	1.0					
SPCPT FP	.00	.01	.01	.03	.07	.08	.08	.09	-.21	-.17	-.15	.06	1.0				
Emo FP	.04	.04	.09	.09	.01	.00	.08	.05	-.12	-.02	-.10	.07	.07	1.0			
ToM FN	-.10	-.09	.01	-.01	-.03	.03	-.01	-.02	-.23	-.30	-.14	.07	.10	.02	1.0		
SPCPT FN	-.07	.01	.03	.05	.03	.03	.07	.00	-.19	-.20	-.14	.00	.19	.09	.09	1.0	
Emo FN	-.07	-.12	-.02	-.03	.02	-.02	.03	.00	-.17	-.18	-.10	.04	.08	-.04	.10	.05	1.0

Note. O 1-4 = openness NEO-FFI items -4; P1-4 = Achenbach psychotism items 1-4; PMAT = Penn Matrix Test; Vocab = Picture Vocabulary Test; List = List Sorting Test; ToM FP = theory of mind task false positives; SPCPT FP = short Penn continuous performance task false positives; Emo FP = emotion recognition task false positives; ToM FN = theory of mind task false negatives; SPCPT FN = short Penn continuous performance task false negatives; Emo FN = emotion recognition task false negatives. Correlations with absolute value > .05 are significant at a two-tailed alpha value of .05.

Table 3
Pearson Correlations Among Sample 2 Measures

Variables	Eccentric	Eccentric Unusual	Perceptual	O-LIFE Pos	MPQ-Abs	BFAS-O 1	BFAS-O 2	BFAS-O 3	BFAS-O 4	Semantic FP	Semantic FN	Auditory FN	Vocabulary	Similarities	Matrix	Block design
Eccentric	1.0															
Unusual	.60	1.0														
Perceptual	.66	.74	1.0													
O-LIFE Pos	.48	.56	.67	1.0												
MPQ-Abs	.65	.74	.79	.61	1.0											
BFAS-O 1	.07	.04	.08	.10	.27	1.0										
BFAS-O 2	.13	.10	.17	.12	.36	.43	1.0									
BFAS-O 3	.16	.21	.18	.23	.32	.57	.41	1.0								
BFAS-O 4	.13	.20	.10	.19	.29	.30	.34	.35	1.0							
Semantic FP	.07	.15	.14	.20	.13	.11	.03	.04	.02	1.0						
Semantic FN	-.19	-.04	-.13	-.10	-.10	-.17	-.05	-.12	-.09	.10	1.0					
Auditory FN	.08	.18	.18	.13	.06	-.07	-.04	-.02	-.11	.13	-.03	1.0				
Vocabulary	.18	.03	.12	.08	.18	.20	.12	.23	.19	.07	.01	.13	1.0			
Similarities	.19	.10	.18	.07	.24	.22	.22	.14	.27	-.08	-.04	-.03	-.25	1.0		
Matrix	.04	.03	-.06	.07	.04	.00	.10	.06	.13	-.02	.05	-.04	-.22	.45	1.0	
Block design	.08	.11	.05	-.05	.10	.19	.10	.05	.16	-.07	.01	-.29	.17	.25	.18	1.0

Note. Eccentric, Unusual, Perceptual = PID-5 psychotism sub-scales; O-LIFE = Oxford-Liverpool Inventory of Feelings and Experiences; MPQ-Abs = Absorption scale from the Multidimensional Personality Questionnaire; BFAS-O 1-4 = item parcels 1-4 for Big Five Aspect Scales Openness; FP = raw false positive rates; FN = raw false negative rates. Correlations with absolute value > .13 are significant at a two-tailed alpha value of .05.

of items. In the Penn Matrix Test, participants completed a set of visual patterns. The National Institutes of Health Toolbox measures of intelligence have shown a high degree of reliability and validity, as indexed by test-retest reliability and associations with gold-standard measures of intelligence (Heaton et al., 2014).

Sample 2. Intelligence was assessed using the Weschler Adult Intelligence Scale, fourth edition (WAIS-IV; Wechsler, 2008). Four subtests of the WAIS-IV were used: block design, matrix reasoning, vocabulary, and similarities. These are the four subtests recommended by Wechsler as a brief but accurate estimate of full-scale IQ.

Behavioral Apophenia Measures (see Figure 1)

Sample 1.

Tricky triangles task (Abell, Happe, & Frith, 2000). Participants were presented a series of computerized animations of shapes interacting either randomly or socially. Participants indicated whether each was random or social. The social condition included a variety of interaction types, such as seducing, coaxing, and mocking. The random condition included shapes that were drifting, bouncing, or moving in other ways that did not imply social interaction. Each participant was presented five random and five social animations, with intermixed presentation order. False positives were operationalized as random trials labeled social. False negatives were operationalized as social trials labeled random.

Penn short continuous performance task (Gur et al., 2010). Participants were presented a series of sets of vertical and horizontal lines that either formed a target letter/digit or a distractor. Participants indicated whether each stimulus was a target or distractor. Items were presented at a rate of one per second, with 300 ms viewing time per stimulus. Thirty-six targets were presented randomly among a total of 360 items. False positives were operationalized as distractors labeled targets. False negatives were operationalized as targets labeled distractors.

Penn emotion recognition task (Gur et al., 2001). Participants were presented a series of 40 faces and asked to identify what emotion each was expressing. Emotion options included happy, sad, anger, fear, and no emotion. For each emotion, eight faces were presented. False positives were operationalized as no emotion trials labeled happy, sad, anger, or fear. False negatives were

operationalized as total number of incorrect responses across the happy, sad, anger, and fear trials.

Sample 2.

Semantic object retrieval task (Assaf et al., 2009). Participants were presented a series of 92 word pairs that were either related or unrelated. Participants indicated whether the two words were related. Examples of related items included popcorn and theater. Examples of unrelated items included books and kernel. False positives were operationalized as unrelated items labeled related. False negatives were operationalized as related items labeled unrelated.

Auditory signal detection task (Galdos et al., 2011). Participants were asked to indicate whether speech was present, in a series of auditory stimuli, presented in four conditions: (a) white noise only, (b) barely audible speech masked with white noise, (c) audible speech masked with white noise, and (d) speech only. Volume of trials was consistent among participants. False positives were operationalized as white-noise-only trials labeled as having speech present. False negatives were operationalized as speech trials labeled noise.

Analysis

Descriptive statistics were calculated for self-report, intelligence, and false-negative and false-positive rates (Table 1). Variables with a skew >2.0 were logarithmically transformed to approximate normality. Structural equation modeling was then used to assess relations among latent factors. Using raw false-positive and false-negative variables for each task, apophenia variables were created for each task by residualizing false-positive scores by regressing them on false-negative scores, resulting in variables representing unique variance of false-positive tendencies for each task. This eliminates the potential confound that poor performance on a task is likely to involve both false positives and false negatives (indeed, the two types of error tended to be positively correlated within each task; Tables 2 and 3). Similar variables were created to represent unique variance in false negatives.

For Sample 1, the corresponding items or tasks were allowed to load onto latent variables for psychoticism, openness, apophenia, and intelligence. Because two psychoticism items from the ASR were strongly semantically related, both entailing that others find the target strange, an a priori decision was made to allow their residuals to correlate. If they were not allowed to correlate, model fit decreased significantly ($\Delta\chi^2 = 265.1, p < .001$). For Sample 2,

Table 4
Model Fit Statistics

Models	χ^2	<i>p</i>	RMSEA	95% CI	TLI
Sample 1					
Model 1 (psychoticism and O)	71.2	<.001	.050	[.038, .062]	.960
Model 2 (psychoticism, IQ, and apophenia)	65.8	<.001	.033	[.022, .044]	.958
Model 3 (O, IQ, and apophenia)	144.9	<.001	.058	[.049, .068]	.897
Model 4 (O-psychoticism, IQ, and apophenia)	228.5	<.001	.047	[.040, .053]	.911
Sample 2					
Model 1 (psychoticism and O)	43.7	.012	.060	[.028, .089]	.971
Model 2 (psychoticism, IQ, and apophenia)	46.4	.048	.046	[.004, .074]	.961
Model 3 (O, IQ, and apophenia)	39.0	.183	.032	[.000, .064]	.961
Model 4 (O-psychoticism, IQ, and apophenia)	125.1	.002	.048	[.029, .066]	.951

Note. CI = confidence interval; RMSEA = root mean square error of approximation; TLI = Tucker-Lewis index; O = openness.

scale scores were used as indicators for psychoticism and openness, and, in models including both psychoticism and openness, MPQ absorption was added as a manifest indicator with cross-loadings from both psychoticism and openness. Intelligence in Sample 2 was indicated by four subtests of the WAIS, with residuals from the verbal intelligence subscales (vocabulary and similarities) allowed to correlate. For Sample 2, given only two tasks, factor loadings for the apophenia factor were constrained to be equal.

Maximum likelihood estimation was used to fit all models. First, confirmatory factor analytic models were fit to examine the relations between openness and psychoticism. Structural equation models were then fit to examine the prediction of apophenia by (a) psychoticism and intelligence, (b) openness and intelligence, and (c) shared variance of openness and psychoticism (henceforth O-P) and intelligence. At the request of reviewers, a number of supplemental models were also fit. First, all of the aforementioned associations were tested without controlling for intelligence and

with intelligence-by-O-P interactions. Second, openness and psychoticism were examined as simultaneous predictors of apophenia. Third, we conducted a set of discriminant validity analyses, using neuroticism and conscientiousness to predict our criterion variables. Finally, we computed models using residualized false negatives as criterion latent variables, as a further test of discriminant validity.

Although a strength of the present study was using multiple tasks simultaneously to assess apophenia, we nonetheless fit a set of auxiliary models to assess the relation of our questionnaire variables with apophenia scores on individual tasks. In addition to testing our hypothesis regarding the advantages of using multiple tasks to assess apophenia, this analysis also provided closer replications of several previous studies (Chen et al., 1998; Fyfe et al., 2008; Galdos et al., 2011). The same latent predictors were used as in the main models, with the observed apophenia scores (residualized false positives) from each task used, in turn, as the criterion variables.

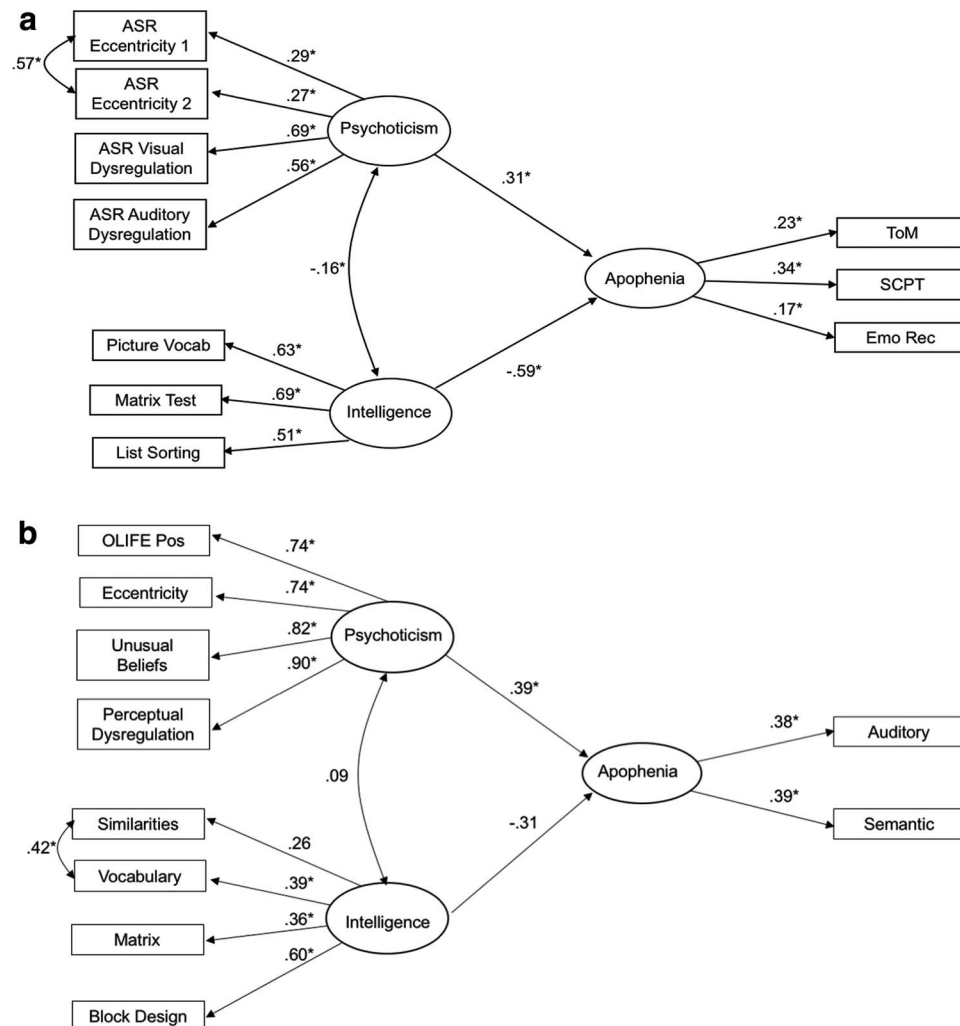


Figure 2. Model of psychoticism, intelligence, and apophenia, Samples 1(a) and 2(b). ASR = Achenbach Self-Report; ToM = theory of mind task; OLIFE = Oxford-Liverpool Inventory of Feelings and Experiences; SCPT = Penn short continuous performance task. * $p < .05$.

Results

Descriptive statistics are presented in Table 1. See Tables 2 and 3 for Pearson correlations among study measures. Structural equation modeling fit statistics for our primary models are presented in Table 4. All models showed acceptable fit using the root mean square error of approximation criterion, with values ranging from .032 to .060. Factor loadings of assigned manifest variables onto their corresponding latent variables were significant, across models, albeit small in magnitude for behavioral indicators of apophenia.

Latent psychoticism was positively correlated with latent openness, in Sample 1, $r = .14$, $p = .005$, and Sample 2, $r = .31$, $p = .001$. Latent psychoticism was positively associated with apophenia, in Sample 1 (Figure 2a) and Sample 2 (Figure 2b). Like psychoticism, openness was significantly positively associated with apophenia in Sample 1 (Figure 3a); the path from openness to apophenia did not reach statistical significance in Sample 2 (Figure 3b), but magnitude of the standardized path coefficient in this model was similar to that found in Sample 1 (which had a larger

N and therefore higher statistical power). If openness and psychoticism were used as simultaneous predictors (while controlling for Intelligence), their individual regression weights were somewhat diminished, and only psychoticism was a significant predictor of apophenia in either sample (Supplemental Figures 1 and 2). This pattern of suppression is consistent with the hypothesis that the shared variance of openness and psychoticism is associated with apophenia. Indeed, in our final set of models, apophenia was positively associated with O-P shared variance in Sample 1 (see Figure 4) and Sample 2 (see Figure 5). The relations of latent scores for O-P and apophenia are visualized using scatterplots in Figure 6.

Associations between O-P and apophenia remained largely consistent across samples and variables, whether or not Intelligence was controlled for (Supplemental Table 1), and these associations were not present for false negatives (Supplemental Table 2). In Sample 1, intelligence was a significant negative predictor of apophenia, in two of three models. Intelligence strongly negatively predicted false negatives across samples and models. Across mod-

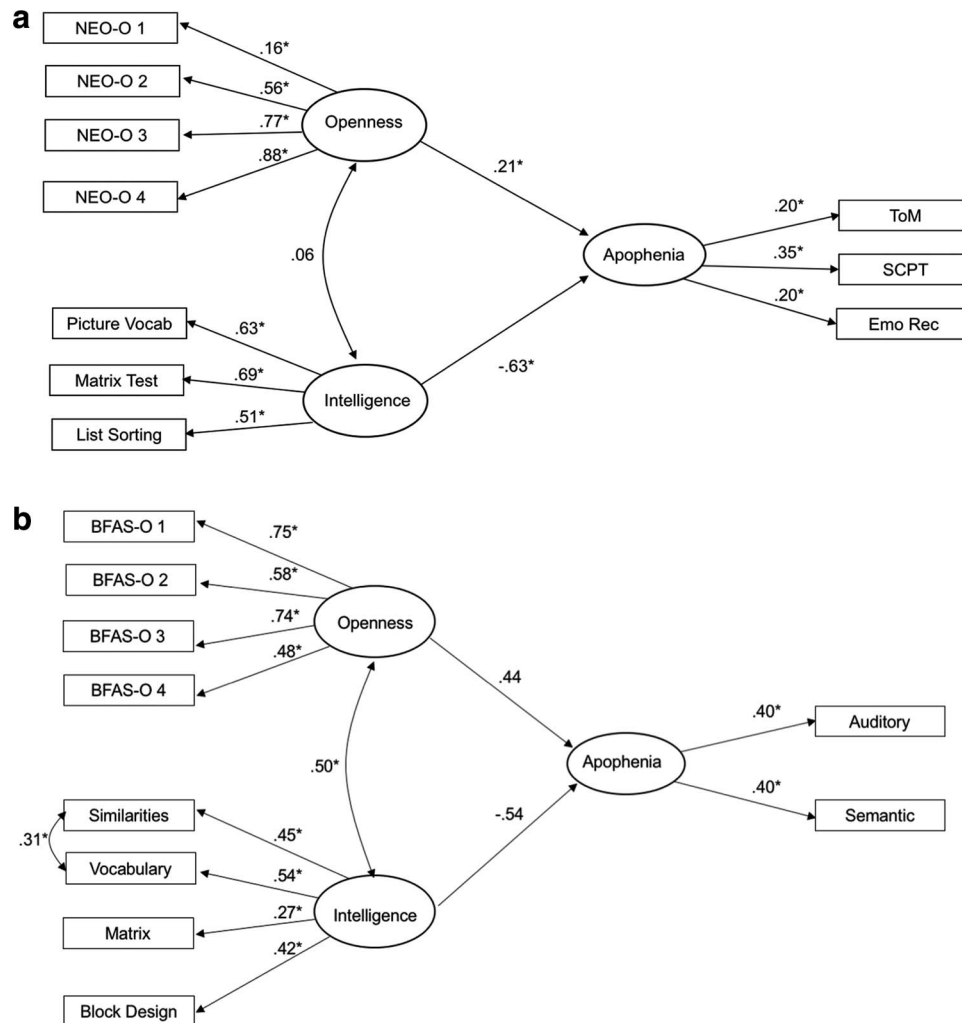


Figure 3. Model of openness, intelligence, and apophenia, Samples 1(a) and 2(b). ToM = theory of mind task; BFAS = Big Five Aspect Scales; SCPT = Penn short continuous performance task. * $p < .05$.

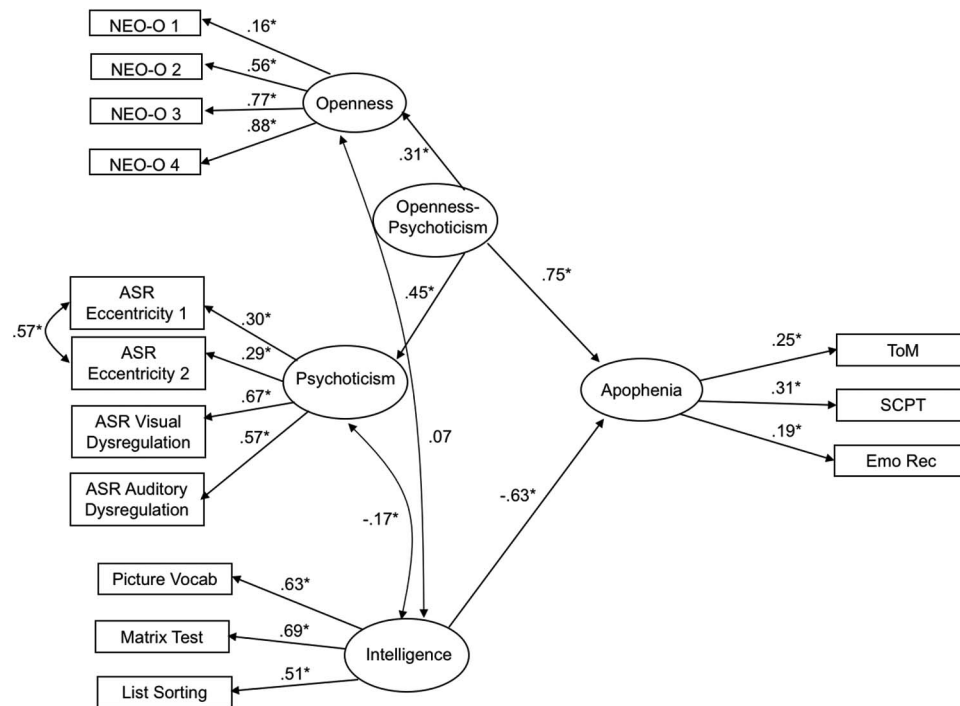


Figure 4. Model of openness-psychoticism, intelligence, and apophenia, Sample 1. ASR = Achenbach Self-Report; ToM = theory of mind task; SCPT = Penn short continuous performance task. * $p < .05$.

els, findings remained substantively identical if we used raw, rather than residualized, false-positive and -negative variables. At the suggestion of a reviewer, we also tested for interactions between intelligence and O-P, in predicting apophenia (Supplemental Table 1). These were mostly nonsignificant across variables and samples, although there was a significant interaction of intelligence and O-P in Sample 1 ($\beta = -.31$, $p < .005$). Tests of discriminant validity showed that apophenia was not predicted by conscientiousness or neuroticism (Supplemental Table 3). Positive associations of psychoticism, openness, and O-P with apophenia were found for the majority of specific tasks, but relations were least robust for the auditory signal detection task (Supplemental Table 4). Path coefficients from O-P variables to observed apophenia variables in the specific task models were smaller in magnitude, compared with our main models containing latent apophenia factors.

Discussion

Findings supported our hypothesis that apophenia, as indexed by false-positive rates, is positively associated with self-report measures of psychoticism and the openness aspect of openness/intellect. Furthermore, associations were specific to false positives because psychoticism and openness were unrelated to false negatives, so our findings do not simply represent a generalized decrement in task performance. Relations were robust and replicable in two samples, across different tasks and, importantly, did not hold for other potentially relevant personality traits, including neuroticism and conscientiousness. Standardized regression coefficients for predictions of apophenia by shared O-P variance were

high, ranging from .61 to .75, suggesting apophenia may be a good representation of what openness and psychoticism have in common. Apophenia of the relatively mild sort represented by false positives on behavioral tasks likely reflects core tendencies toward pattern seeking and perceptual sensitivity, which may, in turn, result in openness to implausible patterns. Our findings suggest that apophenia may be a key cognitive process contributing to risk for psychosis. Findings also contribute to the growing body of research that identifies transdiagnostic risk factors linked to normal personality variation (DeYoung et al., 2012, 2016; Kotov et al., 2017).

The current findings replicate and unite previous empirical work. False alarms in digit identification, social triangles, white noise, and semantic association tasks have each independently been found to correlate positively with psychosis-spectrum measures (Chen et al., 1998; Fyfe et al., 2008; Galdos et al., 2011; Mohr et al., 2001). Our results extend these individual studies, suggesting that single-task indicators of apophenia may underestimate the relation between self-reported psychoticism and behavioral apophenia. Indeed, in our present results, effect sizes for associations with individual-task false positives were much smaller in magnitude than associations with latent behavioral apophenia. Future studies would benefit from assessing a range of behavioral apophenia tasks to overcome the limitations associated with task-specific variance.

Although the increased false positives associated with apophenia may seem deleterious, a tendency toward pattern seeking and perceptual sensitivity (which seems likely to underlie apophenia, openness, and psychoticism) could have provided evolutionary

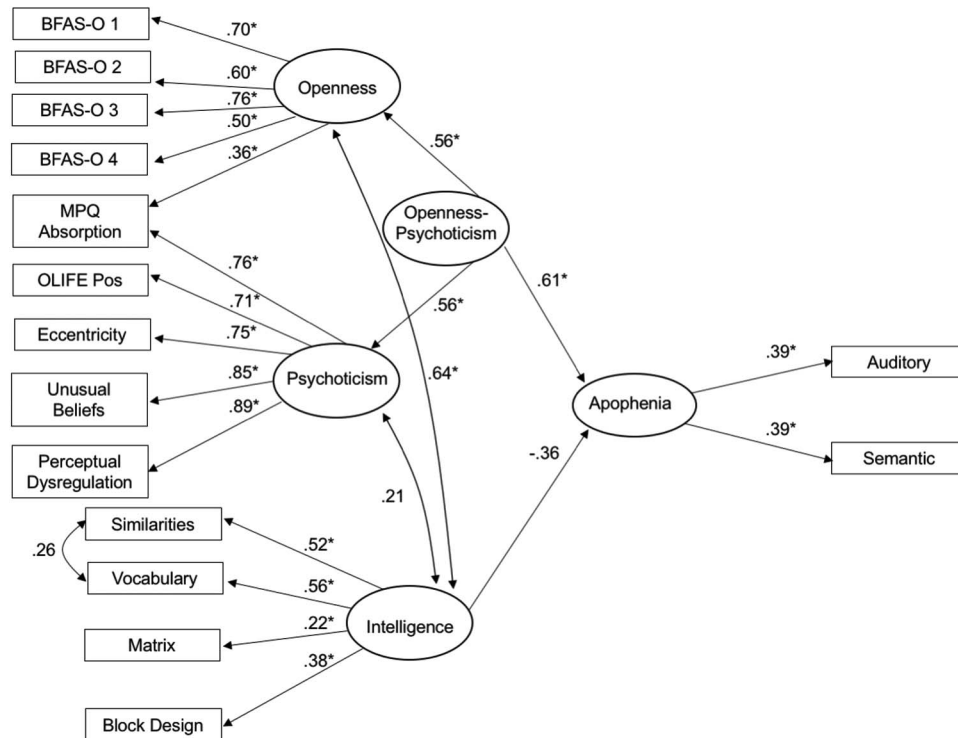


Figure 5. Model of openness-psychoticism, intelligence, and apophenia, Sample 2. BFAS = Big Five Aspect Scales; MPQ = Multidimensional Personality Questionnaire; OLIFE = Oxford-Liverpool Inventory of Feelings and Experiences. * $p < .05$.

advantages. Like any animal, a human being must balance false positives against false negatives in modeling regularities in its experience. Favoring false positives can aid in avoiding threat, even if it sometimes leads to an excess of caution. In contrast, a bias toward false negatives can result in failure to detect actual threats and thus constitutes a threat to survival. Furthermore, favoring false positives may confer advantages in domains in which creative pattern detection is advantageous, for example, among artists, inventors, and even psychics—precisely those populations that are high in openness (Beck & Forstmeier, 2007; Powers, Kelley, & Corlett, 2017). Fitness advantages of high openness may explain the persistence of apophenia throughout the population, despite the detrimental effects of full-blown psychosis. Apophenia might therefore have had a U-shaped relation to fitness, with a moderate level being an acceptable cost for high creativity. Indeed, research suggests both openness and psychoticism predict creativity and creative achievement, regardless of whether or not shared variance with intelligence or intellect is partialled out (Kaufman et al., 2016). Although apophenia and related traits or mechanisms (e.g., openness and pattern seeking) might be associated with certain adaptive characteristics at moderately high levels, when extreme or coupled with other risk factors (such as negative or disorganized symptoms), they may result in severe psychopathology.

Importantly, high intelligence may play a protective role when present in individuals with high openness, allowing better detection of which perceived patterns are likely to be useful rather than spurious (DeYoung et al., 2012). After a false-positive error has

initially occurred, intellectual deficits may contribute to an inability to separate real patterns from spurious ones, possibly leading to suspiciousness, paranoia, and delusional thinking associated with psychosis. Perhaps an optimal balance between type I and type II error rates occurs when an individual has high levels of intelligence as well as openness (which is typical, given that they are positively correlated), allowing high levels of creativity and cognitive exploration, without functional impairment (DeYoung, 2015). This personality profile would likely be associated with a high degree of initial type I errors (because of high openness), paired with effective screening of these errors (because of high intelligence). In other words, some tendency toward apophenia could be advantageous when coupled with intact reality testing. Thus, individuals high in openness who have intact cognitive functioning may exhibit above average functional outcomes, despite a tendency toward apophenia, given that the combination of high levels of pattern seeking and intelligence likely facilitates the generation and application of creativity and innovative thinking.

Results from Sample 1 are consistent with this account because apophenia was negatively correlated with intelligence. In Sample 2, however, there was no relation between intelligence and apophenia, although intelligence was strongly associated with false-negative error rates. This difference might reflect either the fact that different tasks were used or that the second sample was exclusively college students, a group with higher-than-average intelligence. Further research is needed to clarify the possible protective role of intelligence in relation to apophenia and the psychosis spectrum.

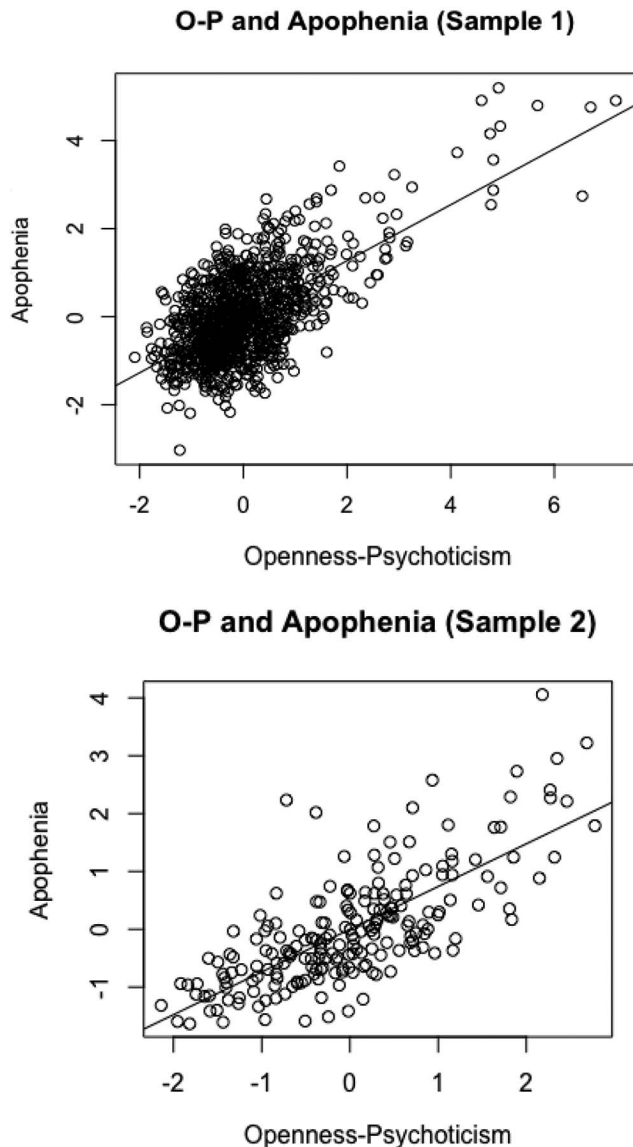


Figure 6. Scatterplots of latent variable relations.

The current study provides insights into the measurement of apophenia using behavioral indicators, an important step in better characterizing cognitive correlates of openness and psychoticism. Apophenia is a scientifically informative transdiagnostic feature seen across a number of disorders characterized by psychosis, including schizotypal and paranoid personality, schizophrenia, and depression and bipolar disorder with psychotic features (Chmielewski et al., 2014; Hanssen et al., 2003; Mishara, 2010; Narayan, Allen, Cullen, & Klimes-Dougan, 2013). Further elucidating the role of apophenia and pattern detection as a cognitive mechanism may prove useful for explaining variation in the tendency to make false-positive errors, in populations ranging from healthy individuals to those with functionally impairing psychiatric concerns. Such an approach is in line with the Hierarchical Taxonomy of Psychopathology conceptualization of psychiatric illness (Kotov et al., 2017) and with the National Institute of

Mental Health's Research Domain Criteria initiative, particularly its cognitive systems dimension (Cuthbert & Insel, 2013). Furthering research into the non-self-report assessment of apophenia using tasks such as those in the current study could allow for research to circumvent problems inherent to questionnaire-based research, an important step for better characterizing correlates and mechanisms underlying the psychosis spectrum, as well as psychopathology more broadly.

Although the current study had multiple strengths, some limitations are worth noting. Despite the fact that our current measures were selected to directly mirror and conceptually replicate past research and have shown association with openness-psychoticism in previous studies and the current sample, it is worth noting that the factor loadings of apophenia variables onto their latent factor were small in magnitude. This is likely to be an unavoidable feature of assessing false positives across a diverse range of tasks, but future work could incorporate additional or even more direct measures of apophenia, such as the Salience Attribution Test (Roiser et al., 2009).

Despite the potential of latent variables comprising multiple task or questionnaire indicators to capture truer estimates of effect size, compared with models using only individual manifest variables, this method also runs the risk of inflating effect sizes beyond their population values, when indicators share only a small portion of variance. Thus, it is important to interpret results of the current study in terms of the general trends seen across models, indicators, and traits (i.e., the consistently demonstrated, yet mild-in-magnitude relations among openness, psychoticism, and apophenia manifest and latent variables), rather than merely focusing on effect sizes of our most comprehensive structural models.

Our measures of openness and psychoticism were self-reported and could be usefully supplemented in future research by peer reports or clinician ratings. Furthermore, we cannot tell how well the current results would generalize to clinical populations, and future research should examine the roles of apophenia in those with active psychosis or at clinical high risk. Finally, although our samples included a variety of psychoticism and personality measures and tested apophenia across a wide variety of tasks, Sample 1 had brief questionnaire measures with relatively few items, and Sample 2, although it had better questionnaire measurement, had a considerably smaller number of participants. These limitations in our current work could be addressed in the future by recruiting additional large samples with extensive, high-quality measures of psychoticism, openness, and apophenia.

Conclusion

The current study advances research on openness, psychoticism, and their possible underlying mechanisms. Apophenia (i.e., false-positive error rate) was shown to be associated with both the openness aspect of openness/intellect and with psychoticism, which is consistent with the role pattern seeking and perceptual sensitivity play in all of these traits. Apophenia, as indexed by behavioral measures of the disposition toward false positives, may provide a useful transdiagnostic construct for studying the cognitive correlates and possible mechanisms of psychosis and related phenomena, across a range of mental disorders and normal personality variation. Understanding how psychoticism relates to nor-

mal personality variation and specific cognitive mechanisms is crucial for advancing our understanding of psychosis risk in the general population. Our current work furthers this aim and also adds to a growing body of literature demonstrating the promise of characterizing the underlying correlates and mechanisms of psychiatric features through the use of large, nonclinical samples.

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