NeuroImage 202 (2019) 116125

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Is perception the missing link between creativity, curiosity and schizotypy? Evidence from spontaneous eye-movements and responses to auditory oddball stimuli

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ARTICLE INFO

Keywords:
Creativity
Curiosity
Schizotypy
Eye-tracking
Eye-gaze
Salience
Perception

ABSTRACT

What is the relationship between creativity, curiosity, and schizotypy? Schizophrenia-spectrum conditions and creativity have been linked to deficits in filtering sensory information, and curiosity is associated with information-seeking. This raises the possibility of a perception-based link between all three concepts. Here, we investigated whether the same individual differences in perceptual encoding explain variance in creativity, curiosity, and schizotypy. We administered an active auditory oddball task and a free viewing eye-tracking paradigm ($N = 88$). Creativity was measured with the figural portion of the Torrance Tests of Creative Thinking (TTCT) and two self-report scales. Schizotypy and curiosity were measured with self-reports. We found that creativity was associated with increased reaction time to the rare tone in the oddball task and was positively associated with the number and duration of fixations in the free viewing task. Schizotypy, on the other hand, showed a negative trend with the number and duration of fixations. Both creativity and curiosity were positively associated with explorative eye movements (unique number of regions visited) and Shannon entropy, while schizotypy was negatively associated with entropy. We further compared saliency maps finding that individuals high versus low in creativity and curiosity, respectively, exhibit differences in where they look. These findings may suggest a perception-based link between creativity and curiosity, but not schizotypy. Implications and limitations of these findings are discussed.

1. Introduction

Creative individuals seem to see the world differently, to notice what others overlook and find meaning in what others deem irrelevant. Many explanations for the cognitive abilities of creatives center critically on perceptual processes, specifically the inability to inhibit irrelevant information (Kasof, 1997; Carson et al., 2003; Fink et al., 2012; Zabelina et al., 2015).

Notably, an inability to screen irrelevant sensory information is also observed in individuals with psychosis-proneness or schizotypy (Braunstein-Bercovitz and Lubow, 1998; Wuthrich and Bates, 2001; Gray et al., 2002). This raises the possibility that the same perceptual characteristics that are associated with creativity may also play a role in schizotypy. Unfortunately, these previous investigations have either looked at schizotypes *or* creatives, but have not looked at the possible overlap between the two (Gray et al., 2002; Carson et al., 2003).

Aside from creativity and schizotypy, recent work suggests that curiosity also involves individual variation in perceptual encoding. Given the theoretical connection between curiosity and creativity, and the motivation of highly curious individuals to explore their surroundings and seek novel information, curiosity may be marked by similar individual differences in perceptual encoding as creativity.

The goal of the present study was twofold. The first goal was to clarify the nature of the relationship between creativity, schizotypy, and curiosity. To this end, we administered a well-established performance-based measure of creativity, as well as self-report creativity scales and validated measures of curiosity and schizotypy.

The second goal was to determine to what extent individual differences in creativity, schizotypy, and curiosity are associated with differences in perception. We employed an auditory oddball task which has been used to study anomalies in perceptual encoding in schizotypes but has not yet been studied in the context of creativity nor curiosity.

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https://doi.org/10.1016/j.neuroimage.2019.116125
Received 7 June 2019; Received in revised form 1 August 2019; Accepted 23 August 2019
Available online 25 August 2019

Furthermore, we investigated a fundamental component of the perceptual process—namely, spontaneous eye movements—which is understudied in personality research in general. To our knowledge, this is the first study in which these three personality traits have been included in a single study and examined in the context of perceptual encoding.

1.1. Creativity, curiosity, and schizotypy

Given the role creativity plays in technological progress and cultural evolution, growing public and scientific interest has developed for understanding the mechanisms and factors that support creativity. However, as popularity in this topic increases, the need to clarify the aspects or types of creativity under investigation has become necessary. Creativity is an umbrella term that subsumes various definitions and theoretical perspectives. It can be defined as a product, a process, an identity or a personality type (Caniëls et al., 2014; Karwowski et al., 2013). For the purposes of this research, we limit our definition of creativity to an individual's capacity to generate original and interesting ideas.

Creativity has previously been linked to both schizotypy and curiosity in separate lines of research. Schizotypy is a trait characterized by less severe symptoms of schizophrenia. Of particular relevance to creativity are the *positive* symptoms of schizotypy, which include magical or delusional beliefs and unusual perceptual experiences. These symptoms are now known to exist on a spectrum (Ettinger et al., 2012), with less severe characteristics occupying a range of "normality" and more severe symptoms characterizing schizotypal personality disorder, or at the farthest extreme, schizophrenia. Visual artists have been observed to exhibit higher schizotypal characteristics compared to non-artists (Burch et al., 2006) and laboratory-based studies show that individual differences in schizotypy correlate with measures of creativity using performance-based tasks (Folley and Park, 2005), self-report scales, (Batey and Furnham, 2008), and even measures that capture the phenomenology of creativity (Nelson and Rawlings, 2008).

Recent empirical work also supports the relationship between curiosity and creativity. Curiosity is defined as the desire for knowledge and is characterized by a strong motivation for exploration and novelty seeking (Berlyne, 1957; Litman, 2005). Curiosity is an important characteristic of the broader personality trait openness to experiences (McCrae, 1987), which has frequently been shown to correlate with creativity (e.g., McCrae, 1987; Feist, 1998; McCrae and Costa, 1997; King et al., 1996; Furnham and Bachtiar, 2008; Silvia et al., 2009b; Kaufman et al., 2016). It has also been theorized that the more narrowly defined trait curiosity is on its own fundamental to creativity (Litman et al., 2005), although empirical support for this relationship is very limited (Hunter et al., 2016; Hardy III et al., 2017). Curiosity has been linked with self-reported creativity (Karwowski, 2012), while a recent study suggests that curiosity might predict the quality and originality of solutions in a problem-solving task (Hardy III et al., 2017) and a divergent thinking task (Hagtvedt et al., 2019). However, to our knowledge, no work has investigated the degree to which curiosity predicts creative performance on commonly used and well-established creativity tasks, such as those from the Torrence Tests of Creative Thinking (TTCT; Cramond et al., 2005). In the current study, we are interested in *epistemic curiosity*, or knowledge-seeking, as well as *perceptual curiosity*, the tendency to show interest in novel sensory experiences.

1.2. Individual differences in eye movements

Where a person looks, and for how long, can reveal a great deal about what is capturing their attention and can give insights into their motivation (e.g., Hoffman and Subramaniam, 1995; Wadlinger and Isaacowitz, 2006; Duchowski, 2007; Rayner, 2009). Despite this, past research examining natural eye movement behavior as a function of higher-level cognitive or personality traits is very limited. Recently, however, researchers have begun to tap this powerhouse of information, and have revealed that eye movements alone can predict traits from the Big Five personality Inventory (Hoppe et al., 2018) as well as other personality characteristics such as optimism (Isaacowitz, 2005; Peters et al., 2016) and negative attitudes (Mele et al., 2014).

Where we direct our eyes and allocate our limited attention depends in large part on what is most salient in our environment (Jensen and Kapur, 2009; Parr and Friston, 2017). Salience attribution, the process by which certain sensory information becomes prioritized over others, is thought to involve the "reward circuit", a mesolimbic pathway connecting the midbrain to the ventral striatum via dopaminergic projections (e.g., Berridge and Robinson, 1998; Horvitz, 2000). Salience attribution is critical for learning and survival and, because it is ultimately in the service of motivating action, is also referred to as *motivational* or *incentive* salience (Berridge and Robinson, 1998; Berridge, 2012; Cunningham and Brosch, 2012).

Recent advances in the study of schizophrenia-spectrum conditions have led to groundbreaking work revealing that dysfunctional salience attribution may lead to the attribution of meaning and prominence to irrelevant information; over time this can lead to the development of schizophrenic symptoms (Palaniyappan et al., 2013). This elegant framework, known as the *aberrant salience hypothesis*, makes a direct link between the striatal dopamine dysfunction present in schizophrenics to the cognitive level characteristics (Kapur, 2003; Ceaser and Barch, 2016)—namely delusional or magical beliefs, eccentric ideation, and perceptual aberrations (e.g. apophenia). Growing support for this model comes from computational, behavioral, and neurobiological investigations among patients with schizophrenia and healthy individuals scoring high on measures of schizotypy (Jensen et al., 2008; Fletcher and Frith, 2009; Corlett and Fletcher, 2012; Murray and Jones, 2012; Irwin et al., 2014; Taurisano et al., 2014; Kirschner et al., 2016).

Due to the relevance of eye movements in salience attribution processes, the relative dearth of research linking natural, self-driven eye movement behavior to schizophrenia-spectrum symptoms is surprising. Research to date has instead been largely limited to the examination of smooth pursuit eye tracking deficits using task-based paradigms (see meta-analysis, O'Driscoll and Callahan, 2008) or lateral asymmetries in eye movement behavior (Simpson and Thomas, 2018). These paradigms, however, do not target the key question of whether differences in visual salience attribution are present. Furthermore, given the robust relationship that has been previously found between creativity and schizotypy, the aberrant salience hypothesis could plausibly be extended to understanding shared mechanisms that may underlie these traits.

It has recently been theorized that curiosity can also trigger incentive salience, which may underlie its "seductive power" to motivate thought and behavior (Lau et al., 2018). Indeed, curiosity shares many of the characteristics of salience attribution processes; it primarily functions to facilitate learning (Marvin and Shohamy, 2016), it involves prioritizing some information over others, and it motivates action and behavior (Foley et al., 2014). Furthermore, like incentive salience, curiosity-driven behavior has also been linked to mesolimbic dopamine activation in the reward circuitry (e.g., Wittmann et al., 2008; Jepma et al., 2012).

Curiosity has long been assumed to be reflected in exploratory eye-movements (Daffner et al., 1992 & 1994); however, it should be noted that using eye movements as a proxy for curiosity may be premature given the scarce foundational work examining curiosity and natural eye movement behavior. Two studies that have examined eye movement behavior in connection with curiosity (Risko et al., 2012; Hoppe et al., 2018) used both a measure of perceptual curiosity (e.g. "when I see a new fabric, I like to touch and feel it") and a personality measure of curiosity (e.g. "I like to do things that are a little frightening"). Risko et al. used correlational techniques with single eye movement metrics (e.g. number of regions visited), while Hoppe et al. employed machine learning to predict large sets of eye movement features in a data-driven fashion. Neither methods detected differences in eye movements as a function of general trait curiosity, but they did find that perceptual curiosity predicted certain eye movement metrics.

Even more limited eye tracking research has examined epistemic, or knowledge-based, curiosity, despite the strong relevance this trait has to information seeking. A recent exception involved inducing epistemic-based curiosity via the presentation of trivia questions (Baranes et al., 2015). Individuals' state curiosity (about the answers) was found to be associated with anticipatory gazes to the location of the answer. However, the role eye-movements play in task-driven versus open-ended contexts may differ in important ways, as task-driven behaviors may recruit different mechanisms (Gottlieb et al., 2013). Therefore, more research is necessary to determine the extent to which trait epistemic curiosity drives natural (i.e. not task driven) eye movements, and to elucidate the differences that may exist between this type of curiosity and perception-based curiosity.

Given the role salience plays in directing eye movements and the plausible relevance of these processes to curiosity, schizotypy, and creativity, this study aims to examine natural eye movements as a function of these traits. In the context of vision science, salience is typically quantified using computational models which measure the pixel-level (bottom-up) features of images in a scene. However, modern vision research has established that affectively charged or meaningful (top-down) stimulus also guide attention (Xu et al., 2014), and indeed can even better predict natural eye movements than traditional salience models (Henderson et al., 2009; Henderson and Hayes, 2017). In the present study, we therefore consider salience as a top-down factor as well, in that different individuals ascribe saliency differently. We employ a free viewing task, as it creates the opportunity for an individual to freely explore an image; participants can choose to examine the whole scene or focus on just a few salient features. We use multiple approaches to explore whether differences exist in basic eye movement metrics, such as the number of unique regions fixated and duration of fixations, as a function of schizotypy, creativity, and curiosity.

To investigate individual differences in salience attribution we use two measures which both directly and indirectly tap this process. First, we compute the Shannon entropy for each participant's eye-tracking data to examine the degree of exploration individuals exhibit when viewing images. Shannon entropy is a way to quantify the complexity of individuals' fixation patterns and captures how much individuals explored the images. A lower entropy value is associated with a more ordered or systematic gaze pattern, whereas a higher entropy value is associated with a more random, unpredictable, and exploratory scanning pattern. We also explicitly explore salience by comparing the saliency maps (i.e. heat maps representing the regions fixated in a scene) of individuals grouped by high or low scores on curiosity, creativity, and schizotypy, respectively.

By employing these techniques, we show for the first time that variations in an individual's eye movements and assignment of visual salience predict variation across these personality traits.

1.3. Responses to salient auditory cues

During oddball tasks, participants are presented with a continuous stream of stimuli and must detect the presence of a salient (i.e. rare, or oddball) stimulus presented at pseudorandom intervals. Typically, participants exhibit a decreased reaction time to the oddball and a prominent P300 spike in event-related potential (ERP) studies; these responses characterize the oddball effect. An abnormal response to rare tones in auditory oddball tasks is one of the most replicated findings in modern schizophrenia research (Jeon and Polich, 2001; Gaebler et al., 2015). The abnormal oddball response exhibited by schizophrenics is reflected by an increased reaction time and reduced ERPs in response to oddball stimuli (compared to reaction time and ERPs found in control participants) (Kiehl and Liddle, 2001), as well as abnormal hemodynamics during oddball detection (Kiehl et al., 2005). This research has been extended to individuals scoring highly on measures of schizotypy (Mannan et al., 2001; Sumich et al., 2008).

Given the robust research linking auditory oddball abnormalities to schizophrenia-spectrum conditions, and the overlapping performance in perception-based tasks between creative and schizotypal individuals, it is plausible that performance on the oddball task would overlap between these two traits. However, auditory oddball effects have not been studied in the context of creativity. This task has also not been explored in the context of curiosity, despite the role curiosity plays in driving novelty directed behavior. The present study thus aims to determine whether a similar pattern of performance exists as a function of curiosity and/or creativity, as observed in the context of schizophrenia-spectrum conditions.

1.4. Summarized objective

In short, we explored whether perceptual differences correlate with schizotypy, creativity, and curiosity using two perception based tasks—an auditory oddball task and a free-viewing eye-tracking task.

We examined basic eye movement metrics (e.g. number and duration of fixations), as well as differences in Shannon entropy and saliency maps. Additionally, we examined whether schizotypy, curiosity, and/or creativity predict the number of unique (different) locations visited in a given image.

Our prediction was that high levels of epistemic and/or perceptual curiosity would predict an increase in entropy, an increase in the number of regions visited, and an increase in the number of fixations. Given the relative dearth of eye-tracking research on creative and schizotypal individuals, our investigations were purely exploratory for these traits; however, we were interested in exploring whether there would be overlap in the pattern of perceptual characteristics displayed by curious, creative, and schizotypal individuals.

Furthermore, given previous demonstrations of a diminished oddball effect in healthy individuals scoring high in schizotypy, we explored whether differences in the oddball effect similarly occur as a function of creativity and curiosity. Given the known relationships between creativity and schizotypy, we specifically predicted that performance on the oddball task may overlap between these two traits.

2. Methods

2.1. Participants

96 undergraduates at the University of California, Santa Barbara participated in this study in exchange for course credit. However, due to technical difficulties, eye-tracking data were obtained for 90 of the 96 participants. Furthermore, 2 participants did not complete the creative drawing task. Therefore the analyses are based on 88 individuals (52 females) to maintain a consistent sample of participants.

As the sample consisted of college undergraduates, participants were relatively homogenous in terms of age ($M = 19.1$, $SD = 1.4$) and highest level of education (61.4% reported high school or equivalent, 35.2% some college, and 2.3% college graduate).

The study was approved by the university's internal review board and conducted in accordance with the Declaration of Helsinki.

2.2. Measures

2.2.1. Personality measures

The Epistemic Curiosity Scale (EC; Litman and Spielberger, 2003) was used to measure curiosity. This 10-item scale was designed to capture individual differences in the desire to learn, which is thought to be driven by a predilection for novel information, or a desire to close a perceived knowledge gap. Cronbach's alpha has been reported as .85 (Litman and Spielberger, 2003). The Perceptual Curiosity Scale (PC; Collins et al., 2004) was also included. This scale captures individuals' interest in their sensory surroundings. Cronbach's alpha has been reported as .87 (Collins et al., 2004).

The Magical Ideation Scale (Eckblad and Chapman, 1983) was used to measure delusional thinking, a key positive symptom of schizotypy. This

30-item true-false scale is one of the 5 subscales in Wisconsin Schizotypy Scales. These are internationally used instruments for the assessment of schizotypy and have been shown to display sound psychometric properties (Kwapil et al., 2007). Cronbach's alpha for the scale has been reported as .82-.85 (Eckblad and Chapman, 1983). This subscale was of particular interest as previous research indicates that it predicts hyperacusis, or sensitivity to hearing (Dubal and Viaud-Delmon, 2008), in addition to creativity on a host of assessments (Schuldberg et al., 1988; Mohr et al., 2001; Badzakova-Trajkov et al., 2011; Dasse et al., 2015).

Creativity was measured using a performance task and two self-report questionnaires. Creativity measures were presented in random order and the instructions were delivered via computer. The performance-based task was the "Incomplete Figures Task" which makes up part of the figural portion of the Torrance Tests of Creative Thinking (TTCT; Torrance, 1972). In this task, participants are given a sheet of paper with four boxes. Inside each box are a few vague lines. Participants are asked to imagine what these lines were the beginning of and to complete the drawing in any way they wish, along with the specific instruction to be creative. They were given 10 min to complete the task.

Additionally, two self-report creativity questionnaires were used: the Creative Behaviors Inventory (CBI; Dollinger, 2003), a 28-item scale measuring how frequently participants have engaged in day-to-day artistic creative behaviors such as writing poems or painting an original picture, and the Creative Personality Inventory (CPI; Kaufman and Baer, 2004), a 20-item forced choice scale listing characteristics that distinguish creative from uncreative individuals (e.g., "I love to think up new ways of doing things"). Cronbach's alpha for the CBI has been reported as .88 (Dollinger et al., 2007) and it has previously been found to correlate with many other markers of creativity, such as performance in a drawing task (Dollinger et al., 2005) and divergent thinking (Silvia and Kimbrel, 2010). Cronbach's has not previously been reported for the CPI, however, in this study we found it to be 0.77.

2.2.2. *Eye-tracking task*

Eye-tracking data was collected using a Tobii T120 eye-tracking system (Tobii, Sweden) integrated with Tobii Studio 3.4.5 software which controlled for stimulus presentation while recording binocular eye movements at 120 Hz. Participants were seated at between 65 cm away from the screen (according to a distance tracker used in the Tobii software during calibration). After being seated comfortably, participants were verbally instructed to remain as still as possible for the duration of the task. Although a chin rest was not used, the participants were verbally instructed to refrain from moving during the task. Furthermore, to minimize potential shifts in the participants' position, the viewing time was kept short by dividing the images into 3 sets and presenting each in a separate run of about 3 min in length. The order of the three sets was counterbalanced, and a 9-point calibration was performed before each run.

For the free viewing task, participants were asked to view the images naturally in any way they choose. Images were displayed on a computer screen (17 inches), subtending a visual angle of 31° (horizontal) and 22° (vertical). Each image was presented for 8 s, followed by a blank screen with a central fixation cross presented for 2 s.

Visual Stimuli: Three sets of full color images were used, which varied in content and number of visually salient objects. 20 images were taken from a repository of images previously used in eye tracking research (Koehler et al., 2014). These consisted of a series of natural indoor and outdoor scenes, e.g. a bicycle lying on the grass, a bathroom with assorted objects on the counter top. The second set of 22 images were aesthetically interesting in nature, and sourced from the internet. These images were lively in color and in content, such as bright colored lizards or skydivers. The third set of 20 images contained a series of non-representational (abstract, impressionist, expressionist, and surrealist) artworks sourced from the internet, from artists such as Kandinsky and Dali. Please see Fig. 1 for examples of images from each of the three sets.

Fig. 1. Examples of natural, aesthetic, and art images in the top, middle, and bottom row, respectively. Images differ in nature, content and number of salient objects.

2.2.3. Auditory oddball task

Participants were seated in front of a 17″ monitor and were asked to listen to two types of tones binaurally through a set of headphones. Before the task, participants were first exposed to each type of tone; the "standard" tone, a low pitch 500 Hz tone, and the "target" (oddball) tone, a high pitch 1000 Hz tone. Participants were instructed to press the left arrow key when they heard the low pitch tone and the right arrow key for the high pitch tone and to do so as quickly and accurately as possible. Practice trials preceded the task to ensure participant comprehension. Participants were able to move on from the practice trials after getting six trials correct; the number of trials were not pre-established. During the practice trial participants received feedback on their performance, either "Correct", "Incorrect", or "Too slow".

64 target tones were presented quasi-randomly, such that no two target tones appeared consecutively, amongst a series of 256 standard tones; thus, target and standard tones were presented with a probability of .20 and .80, respectively. Accuracy, as well as reaction times to target and standard tones, were collected.

2.3. Data analysis

2.3.1. Eye-tracking metrics

Saccades and fixations were distinguished using a velocity-threshold identification (I-VT) fixation filter that detects fast changes in the gaze point, using a sliding window averaging method. Fixations were defined as eye movements with a minimum duration of 60 ms and with a velocity threshold of 30°/s (Olsen, 2012).

Fixation filtering was performed in Tobii Studio 3.4.5, while data pre-processing and the extraction of eye-tracking metrics were implemented in a series of customized in-house Matlab scripts (v.2018b, The MathWorks, Inc., United States). Scripts involved quality assessment through validity checks from segments with miss-detection due to eye-blinks, off-screen fixations, and individual pupil characteristics. Statistical analysis was performed only in image segments with validity superior to 75%. The number and duration of fixations were calculated.

We also calculated the number of regions fixated in each image, which reflects how spatially spread the fixation locations were (https://paperpile.com/c/wZG8yK/eJOEY+ZDSV4 Malcolm and Henderson, 2010; Risko et al., 2012). For this analysis, we defined 64 regions of interest (ROI) based on an 8 × 8 matrix, and for each fixation map, the number of regions fixated for each scene was then totaled.

2.3.2. Shannon entropy

The number of regions fixated reflects how many regions were visited, but not how often. Therefore, regions fixated more than once also count as one. To take into account the frequency with which each region was fixated, we calculated the Shannon entropy of the fixation map, per image. In this context, higher entropy corresponds to a more exploratory viewing pattern, while lower entropy reflects a more spatially constrained visual pattern (Krishna et al., 2018).

The Shannon entropy is defined as:

$$S = -\sum_i p_i \cdot log_2(p_i),$$

where p_i denotes the probability of a certain ROI (*i*) being visited by a fixation.

To further explore the relationship between creativity, curiosity and Shannon entropy, each trait was binned into two score ranges. The binning was performed in a data-driven fashion with scores below the 33rd percentile or above the 66th percentile assigned low and high score ranges. A *t*-test was run to determine whether these groups differ.

2.3.3. Visual saliency maps

Shannon entropy fails to detect differences with respect to which regions were explored by each group. In other words, it does not capture whether observers from different groups (high and low) explore the *same* or *different* regions of the image. To investigate this question, we used a measure of agreement that reflects how well the observers within the same group agree in terms of explored locations with respect to observers selected between the two groups. A similar approach has been taken in a study discerning visual saliency maps across age groups (Krishna et al., 2018).

Saliency maps were constructed by convolution of the fixation maps with a bi-dimensional Gaussian function. We used the area under the curve (AUC) as a metric for saliency maps comparisons (https://paperpile.com/c/wZG8yK/G9eed Le Meur and Baccino, 2013). The AUC reflects how well a saliency map from a group of observers (source map) predicts the fixation map from another group (target map). For within-group comparisons, we used fixations from half of the individuals in the low group to build source maps, and the fixations from the other half of individuals in the same group to form target maps. For between-group comparisons, half of the individuals in the low group were used as source maps while half of the individuals from the high group formed the target maps. These comparisons were made for each image separately. To prevent sampling bias, 100 different maps were built (for each image) by randomly sampling each group (source and target) with replacement (i.e. bootstrap). The average AUC across all images provided the AUC used for statistical comparisons. From this analysis, smaller AUC values are related to a poor agreement between source and target maps, while higher AUC values are related to better agreement.

3. Results

3.1. Personality data

Each of the four drawings from the Incomplete Figures drawing task was scored by two trained research assistants on creativity on a scale from 1 (not at all creative) to 5 (extremely creative). Excellent inter-rater reliability was found, (ICC) $r = 0.96$, thus the raters' scores were averaged. The relationships between creativity scores and the other personality variables are shown in Table 1. Notably, epistemic curiosity was significantly correlated to all three creativity measures, the performance-based drawing task and the two self-report questionnaires, with a strong correlation to creative personality. In opposition to previous research and our own predictions, there were no significant correlations between scores on the Magical Ideation scale and the creativity measures.

3.2. Eye movement results

3.2.1. Eye movement and personality measures

Eye movement data is reported across all three datasets as there were no major differences in the patterns of findings dependent on the type of image set (neutral, aesthetic, or art). Pearson's correlations between scores on the curiosity measures, magical thinking (MI), creativity measures and the four eye-tracking metrics—the number and duration of

Table 1
Descriptive statistics and correlations between the Epistemic Curiosity (EC), Perceptual Curiosity (PC), Magical Ideation (MI), creativity score from the figural portion of the Torrance Tests of Creative Thinking (TTCT: F) and the two creativity measures, Creative Behaviors Inventory (CBI) and Creative Personality (CP) scales. ** represents significance of $p < .01$ and * represents significance of $p < .05$.

	Mean	*SD*	EC	PC	MI	TTCT: F	CBI	CP
EC	2.74	.56						
PC	2.89	.52	.31**	–		.		
MI	4.41	.35	.11	.08	–			
TTCT: F	2.59	.59	.23*	.21*	-.01	–		
CBI	1.75	.47	.30*	.31**	.16	.22*	–	
CP	3.50	.52	.61**	.43**	.11	.27**	.36**	–

Table 2
Pearson's correlations between the eye-tracking metrics— number of fixations (# Fix), duration of fixations (Dur. Fix.), number of regions fixated (# Regions), and Shannon entropy (Entropy)— with the personality metrics Epistemic Curiosity (EC), Perceptual Curiosity (PC), Magical Ideation (MI), the creativity score from the figural portion of the Torrance Tests of Creative Thinking (TTCT: F), and the two self-report creativity scales: Creative Behaviors Inventory (CBI) and Creative Personality (CP). Spearman's correlations are given for duration of fixations (Dur. Fix.) due to non-normality. The *p*-values are italicized in parentheses. Bolded items indicate significance at p < .05 level. Asterisk indicates significance after Bonferroni adjustment, i.e. significance at the *p* < .0125 level.

Measure	EC	PC	MI	TTCT: F	CBI	CP
# Fix.	.15 (*.18*)	.02 (*.86*)	-.19 (*.073*)	**.22 (*.042*)**	.17 (*.11*)	.07 (*.50*)
Dur. Fix.	.12 (*.28*)	.10 (*.36*)	-.02 (*.83*)	.20 (*.056*)	-.16 (*.13*)	.16 (*.14*)
# Regions	**.26 (*.016*)**	.02 (*.83*)	-.20 (*.060*)	**.24 (*.027*)**	.18 (*.092*)	.17 (*.11*)
Entropy	**.24 (*.025*)**	-.03 (*.74*)	-.17 (*.12*)	**.28* (*.010*)**	.20 (*.071*)	.12 (*.28*)

fixations, regions visited, and Shannon entropy—are provided in Table 2. For descriptive statistics of the eye tracking metrics, see Table 3.

There was a significant correlation between creativity on the figural drawing task and the number of fixations, number of regions visited, and Shannon entropy. The relationship was trending positively for duration of fixations. Epistemic curiosity was similarly positively correlated with number of unique regions fixated as well as with Shannon entropy. Notably, the correlations between the eye movement metrics and schizotypy were all in the negative direction. Although none of the correlations reached significance, there was a negative trend for number of fixations, as well as number of regions visited, $r = -.19$, $p = .07$ and $r = -0.20$, $p = .06$, respectively. There was also a trending positive correlation between average scores on the CBI and entropy, $r = 0.20$, $p = .07$, as well as a weaker trend for number of regions visited, $r = 0.18$, $p = .09$. Against our predictions, perceptual curiosity was not significantly correlated to any of the eye movement metrics.

It should be noted that these analyses were exploratory, as we did not have specific predictions about which types of eye movements would correlate with our trait measures of creativity, curiosity and schizotypy. Exploring multiple outcome measures raises the risk of false discoveries or Type 2 errors. However, when venturing into a new area of research, false negatives are equally undesirable as false discoveries. Given the trade-off between risk of Type 2 and Type 1 errors (see Schulz and Grimes, 2005; Streiner and Norman, 2011; Armstrong, 2014), we report exact p-values and, for reference, we also include a Bonferroni adjusted alpha criterion that controls for the number of eye-tracking measures ($p < .0125$). As can be observed, only one correlation reaches significance at the Bonferroni corrected alpha level– that between creativity on the TTCT and Shannon entropy.

For heat maps of sample participants with high and low number of fixations as a function of creativity, see Fig. 2.

3.2.2. Saliency maps

Fig. 3 shows within-group (e.g. low scoring vs low scoring) and between-group (low scoring vs high scoring) AUC values for all independent variables. For a given image, the AUC informs how precisely the fixation map from the target group predicts the saliency map from the source group. It is expected that significant differences in AUC from these two measurements reflect differences in fixation distributions between the low and high groups, suggesting that individuals from one group look at different places on the images, compared to the other group. Furthermore, higher AUC values are expected for within-group comparison, as this would imply that the fixation locations of individuals from the same group (within-group) are more consistent than the fixation locations of individuals from different groups (between-group).

Table 3
Mean and SD (in parentheses) for the four eye movement metrics.

Measure	Mean (SD)
# Fix	21.22 (3.54)
Dur. Fix.	7496.46 (291.75)
# Regions	13.00 (2.37)
Entropy	.58 (.096)

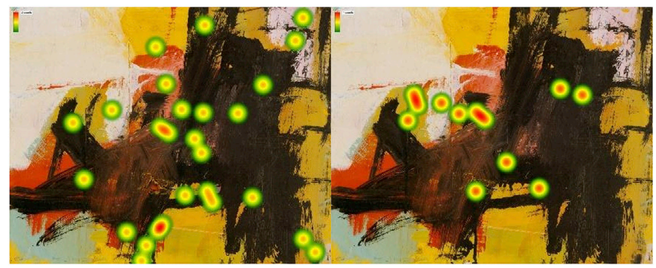

Fig. 2. Sample heat maps illustrating differences in the number of fixations in highly creative (left) and low creative (right) individuals.

There were significant AUC differences in the Incomplete Figures Task ($t_{122} = -2.29$, $p < .05$), Creative Behaviors Inventory ($t_{122} = -3.06$, $p < .01$), Creative Personality Scale ($t_{122} = -2.22$, $p < .05$), Epistemic Curiosity ($t_{122} = -3.32$, $p < .001$), but not in Perceptual Curiosity ($t_{122} = -0.19$, $p = .85$) nor the Magical Ideation Scale ($t_{122} = -1.14$, $p = .26$) (see Fig. 3).

3.3. Oddball data

To compute the oddball effect, a difference score in reaction time to odd and standard tones was computed, for correct trials only, and then divided by average RT. This metric was used as it expresses variation in reaction time to the oddball tone controlling for individual variation in reaction time. A larger difference score indicates that participants respond more slowly to the oddball. Accuracy was also computed as the sum of incorrect trials. Descriptive statistics of RT and accuracy are shown in Table 5. These variables were run in correlational analyses with figural creativity scores, curiosity, and schizotypy; see Table 4.

Overall, participants showed a significant oddball effect, $t(87) = 4.99$, $p < .001$. Once again, due to the exploratory nature of this test and the multiple comparisons, we report exact p-values and use a Bonferroni adjusted criterion controlling for the number of dependent measures on the oddball task; reaction time and accuracy. Only performance on the TTCT was significantly correlated with RT at this adjusted level; specifically, performance on this creativity task was associated with increased reaction times to the oddball tone. This relationship persisted when controlling for accuracy and both types of curiosity (note, accuracy was very high, an average of only about 7 trials wrong out of 320). In opposition to our predictions, no relationship was found between Magical Ideation and the oddball effect. Furthermore, no differences in reaction time were associated with perceptual nor epistemic curiosity.

4. Discussion

To our knowledge, this is the first study to examine creativity, curiosity, and schizotypy together in the context of perception. Our findings reveal a consistent pattern of relationships between some of these personality measures and eye movement metrics. Performance-based creativity was found to be positively, however weakly, associated with

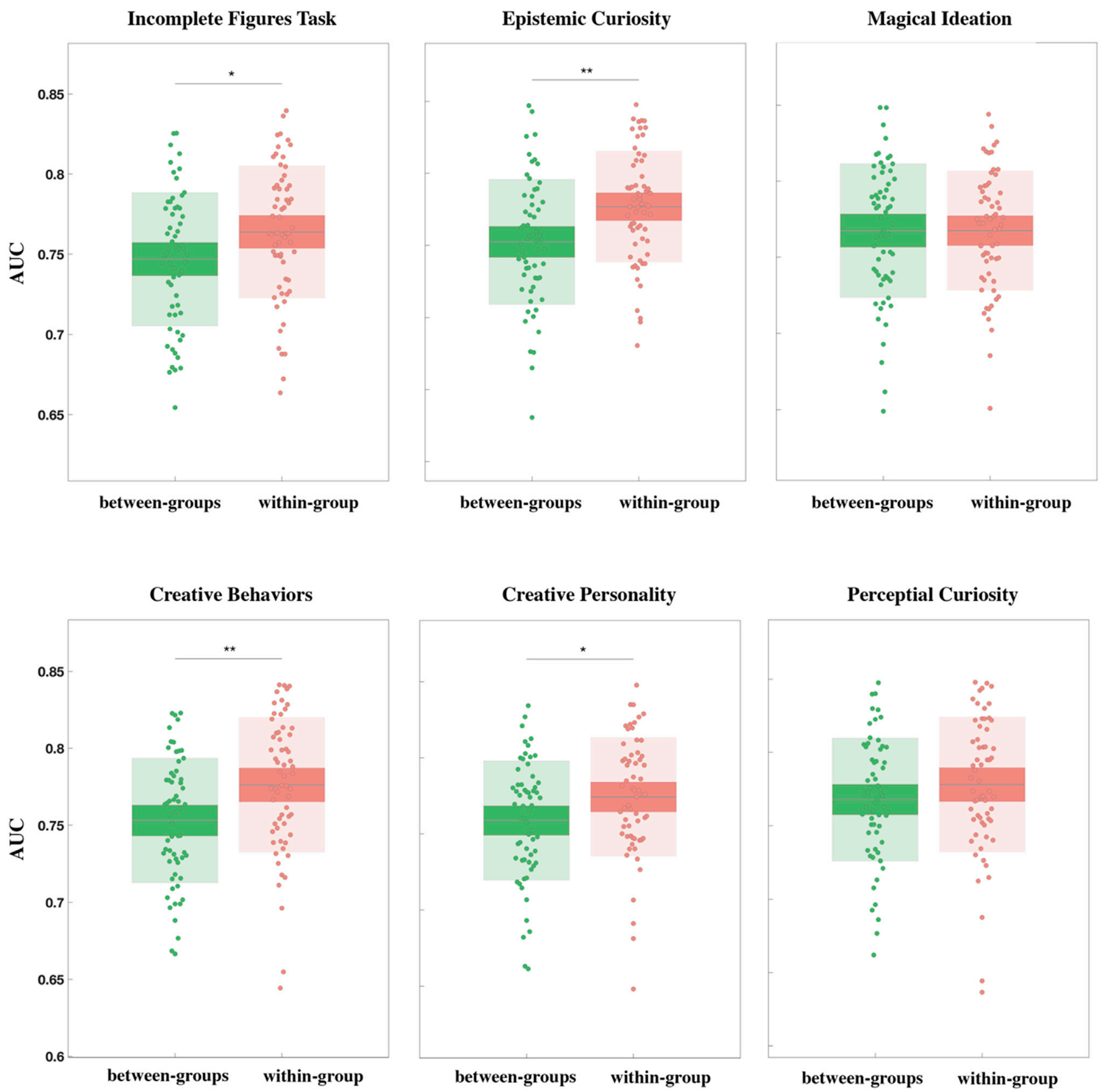

Fig. 3. Saliency maps analysis. Within-group AUC: source and target maps are from individuals in the same group. Between-group AUC: source map from individuals in one group, target map from individuals in the other group. Significant difference was found for some aspects of creativity and curiosity, but not for magical ideation. Average scores, 95% confidence interval, and SD are shown for the features of interest. *p < .05; **p < .01; ***p < .001.

Table 4
Pearson correlations between the RT metric— difference score divided by overall mean RT— with the personality metrics Epistemic Curiosity (EC), Perceptual Curiosity (PC), Magical Ideation (MI), and the creativity score from the figural portion of the Torrance Test of Creative Thinking (TTCT: F). Spearmans' correlations used for accuracy as this metric is non-normal. The *p*-values are italicized in parentheses. Bolded items indicate significance at p < .05 level. Asterisk indicates significance after Bonferroni adjustment, i.e. significance at the *p* < .025 level.

Measure	EC	PC	MI	TTCT: F	CBI	CP
RT	.18	.00	.10	**.27***	.06	-.047
	(*.11*)	(*.10*)	(*.36*)	**(*.012*)**	(*.57*)	(*.67*)
Accuracy	.045	-.01	.038	-.032	.18	.068(*.54*)
	(*.68*)	(*.93*)	(*.73*)	(*.78*)	(*.098*)	

Table 5
Descriptives for the reaction time metric (in seconds) and accuracy (number of incorrect responses out of 320).

Measure	*Mean (SD)*
RT	.044 (.090)
Accuracy	6.6 (9.6)

variation in eye movement behavior across multiple metrics: number and duration of fixations, number of unique regions visited, and Shannon entropy. Epistemic curiosity showed a similar pattern of associations with number of unique regions visited and Shannon entropy, while schizotypy was negatively associated with Shannon entropy. These findings suggest that the way we attend to and engage with visual information may be associated with cognitive level personality traits. However, given the exploratory nature of this study and the non-significant but trending correlations for schizotypy, future research is necessary to confirm or further explore these relationships.

The pattern of associations to the various eye movement metrics may also suggests dissociable relationships between these traits. Both high creativity and high curiosity groups exhibited increased Shannon entropy. Trait schizotypy, on the other hand, showed the opposite pattern; the high schizotypy group demonstrated *reduced* Shannon entropy. Recall that entropy is proportional to the amount of information required in order to describe the behavior of a system, such that higher entropy reflects more complexity and less redundancy. Decreased entropy, on the other hand, reflects systematic fixation patterns; scanning patterns become more ordered. As such, individuals who show higher entropy in their gaze are displaying a higher degree of exploration and unpredictability in what guides their attention.

With this in mind, we could venture to say that creative and highly curious individuals see the world differently in a quite literal sense, in terms of what is capturing their attention and the way in which they scan their environment. This behavior may support creative performance, as suggested by earlier work linking increased processing of (task irrelevant) visual information to creative performance (Agnoli et al., 2015). Another intriguing possibility is that this visual behavior corresponds to the higher level characteristics we associate with creativity and curiosity. The observed variations in vision based behavior may contribute to the disruption of old patterns of thought by increasing the input of novel information. Furthermore, given that the personality trait curiosity has not been found to be related to eye movements (Risko et al., 2012; Hoppe et al., 2018), it could be that the aspect of curiosity that is associated with eye movements has more to do with an interest in semantic information than an interest in diverse experiences and sensation-seeking.

Notably, individuals high in schizotypy displayed a more biased gaze pattern, constrained to particular aspects of a visual scene. This type of inhibited pattern of visual behavior may also be interpreted in light of the cognitive level expression of magical—or "delusional"—beliefs held by these individuals. The aberrant salience hypothesis outlined previously (section 1.2) suggests that magical ideation and other positive symptoms may result from an abnormal assignment of salience to certain features of the environment. Our findings could suggest that individuals high in schizotypy spend their time fixating on regions that have been aberrantly assigned a high degree of salience. Some research also suggests that the tendency to maintain a belief in light of opposing information may be a requisite for the formation and persistence of delusional or magical beliefs (Orenes et al., 2009). This bias against disconfirmatory evidence (BADE) may be reflected as limited hypothesis testing in a visual scene. However, future research is necessary to determine whether performance in tasks that capture BADE relate to this constrained visual behavior.

Given the correlational nature of this study, it remains to be determined whether causal relationships exist between eye movement behavior and these cognitive level phenomena. If causal relationships do exist, it also remains to be determined what direction they are in. It may be that individual differences in salience processing lead to variation in cognitive levels traits, as the aberrant salience hypothesis suggests for schizotypal personality characteristics (Kapur, 2003). In this account, variation in the salience attribution component of perceptual processing may drive differences in thought and behavior. Over time, this may manifest as relatively stable trait level differences. On the other hand, it is possible that cognitive levels traits, such as curiosity, may influence how individuals engage with the world such that the differences that manifest in perceptual behavior are driven by personality.

Additionally, these two accounts may not be mutually exclusive. Early research conceived of salience attribution as hardwired—a product of evolution. However, more recent investigations have focused on the developmental aspect, whereby a history of reward-based learning tunes the visual system based on an individual's past experiences and present goals (Goldstone et al., 2011). Individual differences in experience and personality may then lead to structural changes in the way the visual system maps salience over time, such that an individual's visual and cognitive level processes interact in an iterative fashion. This latter account is supported by developmental models of the visual system which highlight the role that individuals' experiences and goals have in tuning the visual system across the lifespan (Goldstone et al., 2011).

Unfortunately, most studies investigating personality and perception offer correlational designs that do not lend themselves to causal interpretations. Future research should aim to experimentally manipulate creativity and curiosity in order to determine whether associated eye movement behavior can be induced. Future eye-tracking research is also necessary to determine the degree to which perceptual differences in creative and curious people overlap, and to find ways to distinguish the unique features of these two related, but distinct, traits.

We did not find a relationship between eye movement metrics and perceptual curiosity (PC scale), contrary to previously reported findings (Risko et al., 2012; Hoppe et al., 2018). A number of factors could be contributing to the divergent results, including differences in methodology. For instance, we used 62 images presented each for 8 s, whereas Risko et al. used 18 images presented for 15 s. It is possible that perceptual curiosity drives extended interest in an image or continued exploration, which would not be captured in relatively shorter stimulus presentations. Furthermore, we used a mixture of aesthetic, artistic, and neutral images. Though we found no substantial differences in correlations between image types, we cannot say conclusively whether image content interacts with personality type to predict differences in eye movement behavior. Further research is necessary to determine whether image content, number of images, or length of presentation are factors contributing to different results.

Comparisons of the saliency maps suggest that individuals with high and low creativity and epistemic curiosity also differ with respect to *where* they look in the images. We did not find significant AUC differences in the saliency maps of the low and high schizotypy (magical ideation) groups. In other words, saliency maps within the same group were no more consistent than those between the two groups. This could be interpreted to mean that the fixation points from individuals with low and high schizotypy are consistently localized at the most salient locations of the image, or it could mean that there is little consistency between individuals within and across groups.

Our results further indicate that auditory processing of novel information may differ in creative individuals, as observed in the auditory oddball task. Creativity on the drawing task was associated with increased reaction time to the oddball tone; a similar pattern to what has previously been found for patients with schizophrenia (Kiehl and Liddle, 2001; note in this study participants only responded to the target tone). It has been previously suggested that various forms of creativity may be implicated with attention differently. While some creativity tasks require top-down control and are associated with intelligence and executive processes (Benedek et al., 2014), other forms of creativity are associated with "leaky" attentional filters and poor cognitive control (Zabelina et al., 2016; Zabelina and Ganis, 2018), and are more commonly associated with psychopathology. Our findings may suggest that the creativity captured by the figural drawing task is associated with poor cognitive control which accounts for the longer latencies observed for creative individuals when responding to the oddball tone. This result may also indicate a discrepant processing of novel, or deviant, information. Other salience modulation paradigms, such as latent inhibition, should be explored alongside this measure to determine whether overlap in performance exists, considering both have previously been linked to creativity and schizotypy.

A limitation in this study is the relatively homogenous population used, namely, university undergraduates. Indeed, the null finding for schizotypy (i.e. magical ideation) predicting oddball performance could be due to relatively low variance in schizotypy scores. Furthermore, while many studies find differences in ERPs to oddball versus standard tones as a function of schizotypy (Mannan et al., 2001; Sumich et al., 2008), fewer report reaction times (as opposed to ERPs), and some have found no differences in the reaction time oddball effect as a function of schizotypy (Kimble et al., 2000). This study was specifically interested in how cognitive level phenomena that have previously been linked to creativity relate to perceptual differences; therefore, only Magical Ideation was used and not the Perceptual Aberrations scale. Past research has also used these scales together to form a combined "Per-Mag" score.

It should be noted that despite the considerable number of studies reporting relationships between creativity and schizotypy, no relationship was observed using the particular measures used in this study. It may be that other measures of creativity, for instance, real-life creative achievement, would show a more consistent relationship to schizotypy. These other measures of creativity may also be associated with the same perceptual metrics as schizotypy. Therefore, this study cannot rule out the possibility of a visual connection between creativity and schizotypy. Furthermore, given the exploratory nature of this study and the weak correlations between the personality variables and the eye movement metrics, further confirmatory research is necessary to replicate these findings.

5. Concluding remarks

Eye movements are a basic yet fundamental component of the perceptual process. They play a role in how we take in our surroundings, form impressions, learn, and act on our environment from infancy on. In the context of creativity, eye movements determine whether we have the potential to see something unique and interesting in something mundane, just as a sculptor may see a shape hidden in a piece of wood or an engineer may look at a broken mess and see an elegant solution. Studying the basic, fundamental behavior of eye movements can potentially tell us a great deal about how different people perceive their environment, reflect on it and get ideas for how to act on it. Future research should harness this powerhouse of information to explore the relationship between creativity and related traits, such as curiosity, schizotypy, and other personality traits.

This line of investigation should also be extended by using more ecologically valid methods in real world contexts. Although the picture-viewing paradigm is highly prevalent in eye tracking research, a number of important issues have been raised about the validity of drawing conclusions about natural eye movement from observations obtained through these methods (e.g. Tatler et al., 2011). Most paradigms present images for a few seconds, which may cause a change in the strategies participants use to obtain information from the image. Recent technology, such as mobile eye tracking, has created the opportunity to capture eye movement in richer and more natural viewing environments.

Additionally, future research is necessary to clarify the relationship between curiosity and creativity. Despite the intuitive connection between creativity and curiosity, only recently has this relationship been systematically probed and empirical research is still quite limited (Hunter et al., 2016; Hardy III et al., 2017; Hagtvedt et al., 2019). In their definition of curiosity, researchers Kashdan and Silvia (2009) note that "curiosity motivates people to act and think in new ways and investigate, be immersed, and learn about whatever is the immediate interesting target of their attention" (page 368). This definition seems to overlap fundamentally with the features of creative thinking, which is often defined as the ability to generate novel and useful solutions to a given problem. Additionally, curiosity, like creativity, is a fairly broad term and many researchers have called for a more rigorous taxonomy to differentiate the many ways in which curiosity can be expressed. Future research should clarify what features or aspects of curiosity overlap with what specific aspects of creativity, and whether any common variance is explained by differences in perceptual encoding.

Data availability and study materials

OSF registry https://osf.io/vwrd2/?view_only=fce52c8208fa40b688e0248a5e54ceb6.

Funding

This research was supported by a grant from the John Templeton Foundation (#60844). D.B.A. was supported by Fulbright and CAPES foundations.

Acknowledgments

Thank you to Arturo Deza (post-doc Harvard University) for supporting advice.

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