frontiers | Frontiers in Education

TYPE Brief Research Report
PUBLISHED 16 July 2025
DOI 10.3389/feduc.2025.1637218



OPEN ACCESS

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RECEIVED 28 May 2025
ACCEPTED 03 July 2025
PUBLISHED 16 July 2025

CITATION
Blue C, Barr N, Ma B, He H, Cox CT Jr and Seli P (2025) Understanding scientific creativity: an exploratory creativity scale for organic chemistry.
*Front. Educ.* 10:1637218.
doi: 10.3389/feduc.2025.1637218



# Understanding scientific creativity: an exploratory creativity scale for organic chemistry

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Creativity is pivotal for innovation across various domains, including science, technology, engineering, and mathematics (STEM). The present study explores domain-specific creativity in organic chemistry by introducing the Divergent Skeletal Formula Task (DSFT) as a novel measure. The DSFT requires participants to generate constitutional isomers of a given molecular formula, providing an objective quantification of creativity based on the rarity and originality of responses. We investigated the correlations between DSFT performance and established creativity indices—the Alternate Uses Task (AUT) and the Divergent Association Task (DAT)—while controlling for age, gender, and fluid intelligence through partial correlation analyses. The results revealed that correlations between DSFT performance and both AUT Creativity and DAT scores were not statistically significant. However, there was a significant positive correlation between DSFT performance and AUT Flexibility, suggesting that cognitive flexibility is a critical component of creativity in chemistry, even when statistically accounting for age, gender, and fluid intelligence. This finding supports the idea of domain-generality in creativity, indicating that cognitive processes underlying general creative thinking, particularly flexibility, are applicable to specific STEM domains like organic chemistry. Thus, insights from studies on general creativity may be valuable for understanding and fostering creativity in specialized fields, offering practical implications for educational and research settings.

KEYWORDS

**creativity, STEM, chemistry, domain-specificity and generality, divergent thinking**

## Introduction

Creativity serves as the bedrock of innovation and progress across numerous domains, from the arts to the sciences (Amabile, 1996; Sternberg, 2006). Its significance extends beyond individual achievement, fostering societal growth, driving technological advancements, and providing solutions to complex global challenges. Given the important contributions of creativity in advancing these realms, it is perhaps unsurprising to learn that there has recently been a burgeoning interest in the exploration of creativity within STEM fields (e.g., Sternberg et al., 2020; Daker et al., 2022; Beaty et al., 2023). This growing focus highlights the essential role of creativity in these scientific disciplines, catalyzing fresh perspectives, enabling innovative solutions to complex problems (e.g., healthcare advancements, climate change mitigation), and setting the stage for revolutionary discoveries. As STEM fields continue to tackle the world's most pressing issues, it is imperative that we better understand and foster creativity within these fields.

Much of the inquiry into creativity in recent decades has focused on psychometric instruments that are largely divorced from domain-specific knowledge (see Bellaiche et al., 2023). For example, the Alternate Uses Test (AUT; Guilford, 1967), a prevalent tool in psychological studies, prompts participants to conceive 'novel and useful' applications for everyday objects, such as a 'brick.' Creativity scores are then assigned based on each suggestion's originality and utility. Similarly, the Divergent Association Task (DAT; Olson et al., 2021), a more recent but widely adopted measure, evaluates an individual's ability to generate words that are semantically distant from each other. Participants are asked to produce ten words as unrelated as possible, and their responses are scored by measuring the semantic distance among the words within a semantic network, with greater distance suggesting higher creativity levels. Importantly, while these measures have proven invaluable to researchers and the broader field of creativity studies, they predominantly assess domain-general aspects of creativity, emphasizing divergent thinking and verbal flexibility. However, this focus overlooks more specialized forms of creativity, such as those found in scientific disciplines. For instance, the capacity to devise a novel mathematical proof or develop a ground-breaking theory in physics represent types of creativity that these general tests do not adequately capture.

Notwithstanding these measurement challenges, some research has specifically addressed scientific creativity, although these investigations remain relatively sparse compared to those focused on divergent thinking and verbal creativity. One approach in this line of research has been to examine the psychological profiles of eminent scientists in order to gain insights into their creative processes (Roe, 1949). Another approach has involved using a case–control comparison design, wherein researchers examine highly creative scientists by measuring cognitive and personality variables that differentiate them from less creative counterparts (as in the Iowa Study of Creative Genius; Andreasen, 2011). Related work has explored the relationship between scientific productivity and factors like intelligence and personality (Barron and Harrington, 1981), and the cognitive processes involved in aspects of creative scientific thinking (e.g., Dunbar and Blanchette, 2001). In more recent work, scientists have begun to unravel the neural correlates of scientific creativity, both from a structural (e.g., Wertz et al., 2020) and functional perspective (Beaty et al., 2023).

Despite the growing interest in scientific creativity, what remains missing are tasks that index creativity in a quantifiable, systematic way that is amenable to mass administration and easy scoring, yet capture crucial elements of the specifics of scientific creativity (particularly within particular sub-fields of science). Decades ago, Barron (1965) articulated the need for such tests as instrumental in the development of the field's approach to studying creativity more generally:

> "A primary strategic consideration in building tests of creativity derived from the practical need for tests which (a) can be administered to groups of subjects rather than to one subject at a time, (b) can be mechanically scored without the intermediation of a rater, and (c) depend on simple enumeration which can yield frequency distributions readily susceptible of statistical analysis" (p. 13).

In response to this identified gap, and in light of the unique properties of creative problem-solving in chemistry, our study aimed to develop a novel, domain-specific measure of creativity tailored to organic chemistry—The Divergent Skeletal Formula Task (DSFT)—and to assess its possible associations with performance on two gold-standard measures of creativity: the AUT and the DAT. For the DSFT, participants were asked to draw as many constitutional isomers as possible using the molecular formula $C_6H_{12}O$. The constitutional isomers of $C_6H_{12}O$ have an array of chemical and physical properties, which illustrate the complex nature of organic chemistry. The central focus of organic chemistry is understanding these properties and developing frameworks for synthesizing organic molecules. Corey (1991) discussed the importance of "creativity" in organic syntheses. Initially, syntheses tasks that have multiple pathways were proposed for the study, but these would have required more content knowledge. Given much of organic chemistry draws on understanding structure, we opted to focus on structures given the importance of structure in predicting properties and in designing syntheses.

For the DFST, wee then computed a creativity score for each participant by considering (a) how many isomers they generated (i.e., ideational fluency) and the originality (or novelty) of each generated isomer within the set of all images drawn by all participants. Of particular interest to us was whether creative performance on the DSFT correlated with performance on the AUT and/or DAT.

On the one hand, if the DSFT demonstrates significant positive correlations with established measures of creativity, such as the AUT and the DAT, this would suggest that creativity in the domain of organic chemistry shares common features with more general forms of divergent thinking. Such a finding would imply that at least some of the cognitive processes involved in generating novel ideas in organic chemistry are similar to those assessed by traditional, generalized creativity tests. Consequently, insights gleaned from research on these established measures could be applied to the field of organic chemistry. For example, interventions proven to enhance performance on generalized creativity assessments (e.g., Zabelina, 2013) might also be effective in boosting creative output in organic chemistry. Furthermore, the factors known to correlate with divergent thinking could be relevant to creativity within this scientific domain (Beaty et al., 2023). This would be particularly important because understanding these correlates could help identify the key elements that drive innovative problem-solving in organic chemistry. Such knowledge could in turn inform selection of high creative potential candidates, the development of specialized educational programs, and training initiatives aimed at fostering creativity among students and professionals, ultimately leading to breakthroughs and novel solutions to complex scientific challenges.

Conversely, if the DSFT does not correlate with the AUT and/or DAT, this would highlight the distinctiveness of domain-specific creativity in organic chemistry. Such a finding would point to the limitations of using general creativity measures to assess specialized forms of creativity and suggest that the cognitive processes involved in creativity within the domain of chemistry differ significantly from those required for divergent thinking tasks (Baer, 2015; Simonton, 2003). This lack of correlation would be equally important, emphasizing the need for domain-specific creativity assessments in scientific disciplines (Kaufman and Baer, 2004). Further, it would support the argument that creativity in STEM fields involves unique cognitive skills and knowledge bases that general measures cannot capture (Sternberg and Kaufman, 2010). Therefore, regardless of the outcome, the development and implementation of specialized creativity tasks, like the DSFT, are crucial to better understand and foster creativity within particular scientific contexts.

(1) To draw upon existing research and expand creativities studies into the organic chemistry domain our study had two objectives: Develop an exploratory creativity task (the Divergent Skeletal Formula Task, DSFT) in organic chemistry.
(2) Examine the relationship between domain-specific creativity in organic chemistry, as measured by the DSFT, and more general measures of creativity, including the AUT and the DAT.

# Methods

This study was approved by the Duke University Institutional Review Board (IRB protocol number: 2021–0596).

## Participants

We recruited one hundred and fifteen participants, each of whom was enrolled in Organic Chemistry II Lab (CHEM 202 L) at Duke University between January 2022 and January 2023. Eleven participants did not complete at least one of the four tasks administered and, consequently, their data were excluded from all analyses (final $N = 104$, $M_{age} = 19.31$ years; Age Range = 18–26 years; 59.6% female).

# Materials

## The Divergent Skeletal Formula Task (DSFT)

For the DSFT, participants were given 5 min to draw as many constitutional isomers as possible for the molecular formula $C_6H_{12}O$. All isomers had to be drawn using a standard skeletal formula. Participants were reminded that constitutional isomers are compounds with the same molecular formula but different structural formulas. They were also told that all standard bonding conventions should be followed, but instability associated with sterics and bonding angles could be ignored. Finally, they were instructed to disregard stereochemistry, as the molecules would not be scored for 3D representations (ex. enantiomers, diastereomers). Participants were required to draw all structures on paper and were given an additional 3 min to scan and upload a copy of their work into Qualtrics.

Following completion of the study, we computed a creativity score (the Isomer Creativity Score) for each participant, which accounts both for (a) how many isomers they generated (i.e., ideational fluency) and the originality of each generated isomer within the set of all images drawn by participants. To this end, we began by using the software ChemDraw and the website chemspider.com, which indicated that 372 unique constitutional isomers exist for the molecular formula $C_6H_{12}O$ (*Search* ChemSpider, n.d.). However, after filtering out all stereoisomers (i.e., isomers based on positioning in 3D space), 198 remained. Next, we uploaded each handwritten response to the DSFT as an image to Qualtrics. These images were re-drawn with the ChemDraw software and given computer-generated IUPAC[1] names. After naming the compounds, a spreadsheet was created that kept a record of every isomer drawn by each participant. To calculate the probability of drawing any given isomer, the following formula was used:

$$P(I_x) = \frac{number\ of\ times\ isomer\ \text{'x' was drawn}}{total\ number\ of\ participants}$$

Then, an Isomer Creativity Score (ICS) was computed for each participant. This score is the inverse-average of the probabilities for all drawn by an individual:

$$ICS = \frac{1}{\frac{1}{n}\sum_{i=1}^{n} P(I_i)}$$

This inversion allows the ICS to grow larger as participants draw structures that are more statistically infrequent (i.e., original) and as they draw more structures. Thus, this score considers both ideational fluency and originality. Notably, by employing quantitative methods to measure the novelty of each structure compared to the group, the ICS presents as a purely objective measure of originality.

## The Alternate Uses Task (AUT)

To measure divergent-thinking ability, participants were instructed to complete two rounds of a computerized AUT (Guilford, 1967), which was presented via Qualtrics survey software. For the AUT, participants were separately provided two common objects ("newspaper" and "balloon") and instructed to think of as many original and creative uses as they could for these objects. They were encouraged to generate responses that are "creative, useful, and specific to the object." Three minutes were allotted for each of the two objects.

We examined two indices of divergent thinking, flexibility and creativity ratings, which were provided by two independent raters. Flexibility measures how many different categories of uses a person can think of for a single object. This scoring component evaluates the ability to shift one's approach and think of a variety of solutions or uses that are not just numerous but also diverse. For instance, if a participant were to list several uses for a newspaper, such as starting a fire, wrapping a gift, and swatting insects, these responses would each fall into different categories (heating, packaging, and pest-control) and thereby reflect high flexibility. Conversely, if another participant suggested using a newspaper for cutting out articles for a scrapbook, making paper mâché for an art project, and crafting a homemade greeting card, these ideas would fall under the single category of "arts and crafts," showing less diversity in the types of uses, thereby reflecting lower flexibility. To compute Flexibility, the two raters were instructed to take the sum of each participant's unique codes

1 The IUPAC is the International Union for Pure and Applied Chemistry. It is the international authority on chemical nomenclature.

(Alhashim et al., 2020), which were then averaged across the two objects (newspaper and balloon). To determine the inter-rater reliability, we computed the Cronbach's Alpha, which showed good reliability ($\alpha = 0.90$).

Creativity ratings were also provided by two independent raters using a 1 (obvious, ordinary, or intractable) to 5 (very imaginative or recontextualized) scale for uses generated for each of the two objects (Silvia et al., 2008). For each object, and each participant, we computed the average creativity-rating score; we then computed the average of these two averages for a single creativity-rating score for each participant. To determine the inter-rater reliability, we computed the Cronbach's Alpha, which showed good reliability ($\alpha = 0.87$).

## The Divergent Association Task (DAT)

The DAT was administered via Qualtrics as a measure of domain-general divergent thinking. For this task, participants were given 4 min to name ten words that are as unrelated to each other as possible. The words could only be single words and nouns, with no proper nouns or specialized vocabulary/jargon. Additionally, words had to be thought of individually (as opposed to drawing inspiration from one's surroundings).

An algorithm was then used to calculate average semantic distance between the first seven valid words, with related words having a shorter distance between them than unrelated words (Olson et al., 2021). The total score was the transformed average of the semantic distance between the seven words, with higher averages being deemed more creative.

## Fluid Intelligence Scale

To ensure that any observed correlations among the creativity measures were not confounded by underlying cognitive abilities, we measured and controlled for fluid intelligence. This variable represents the capacity to think logically and solve problems in novel situations, independent of acquired knowledge, which could potentially influence performance on the creativity tasks. To measure fluid intelligence, we administered the Fluid Intelligence Scale, which was taken from the Culture Fair Intelligence Test (CFIT; Cattell and Cattell, 1973). For this task, participants were provided 3 min to work through as many sequence-completion questions as they could. The scale consisted of thirteen multiple-choice questions. Each question presented a series of three pictures in a row and the participant selected the fourth image—out of six options—to complete the sequence.

## Procedure

All tasks for this study were presented to participants via a Qualtrics survey. Prior to participation, participants were required to provide electronic informed consent. The study utilized a within-subjects design wherein each participant was exposed to all tasks, the order of which was randomized. The tasks included the DSFT, the AUT, the DAT, along with a measure of fluid intelligence using a scale from the CFIT. Participants completed the survey on their individual computers at a time of their choosing, allowing for flexibility and ensuring that they could engage with the tasks without time constraints beyond those set for each task. Upon completion of all tasks, participants were asked to provide demographic information, which included age and gender. Finally, participants were debriefed about the purpose of the study, and were compensated for their time and effort with either a $15 Amazon E-Gift Card or course credit, depending on their preference.

# Results

## Descriptive analyses and correlations

Descriptive statistics for all primary measures are presented in Table 1. All measures demonstrated good psychometric properties (skewness < 2, kurtosis < 4; Kline, 2011).

Table 2 presents the full correlation matrix for all measures, which provides an overview of the relationships between all variables of interest. This matrix is included for descriptive purposes to allow readers to see the general patterns of association between variables. As this is not the primary analysis, corrections for multiple comparisons were not applied.

## Primary analysis

Of primary interest was whether creativity in the domain of chemistry (indexed via the ICS) correlated with gold-standard indices of creativity (i.e., performance on the AUT and the DAT). To explore this possibility, we examined the correlations among the ICS, AUT Originality and Flexibility Scores, and DAT scores. To ensure that any possible correlations were not driven by age, gender, or fluid intelligence, we conducted a partial correlation analysis that statistically controlled for these variables. Additionally, to account for multiple comparisons, we applied a Bonferroni correction. Given that we conducted three comparisons, the significance threshold was adjusted to $\alpha = 0.05/3 = 0.017$. As can be seen in Table 3, the results

TABLE 1 Psychometric properties for primary measures ($N = 104$).

| Measure | Mean | Range | 95% CI | Skewness | Kurtosis |
|---|---|---|---|---|---|
| ICS | 0.76 | 0.48–0.97 | 0.73–0.78 | −0.41 | −0.54 |
| AUT Flexibility | 5.93 | 2.00–10.80 | 5.52–6.34 | 0.19 | −0.71 |
| AUT Creativity | 2.63 | 1.33–3.67 | 2.55–2.71 | −0.19 | 0.37 |
| DAT | 81.96 | 67.45–95.91 | 80.90–83.02 | 0.06 | −0.30 |
| Fluid Intelligence | 0.53 | 0.08–0.85 | 0.50–0.56 | −0.82 | 1.30 |

ICS, Isomer Creativity Score; AUT, Alternate Uses Task; DAT, Divergent Association Task.

TABLE 2 Bivariate correlation coefficients for all measures ($N = 104$).

| Measure | AUT flexibility | AUT creativity | DAT | Fluid intelligence | Age | Gender |
|---|---|---|---|---|---|---|
| ICS | 0.222* | 0.126 | 0.159 | 0.150 | −0.190 | 0.173 |
| AUT Flexibility | – | 0.310** | 0.170 | 0.073 | 0.066 | −0.022 |
| AUT Creativity | | – | 0.292** | 0.179 | 0.021 | −0.067 |
| DAT | | | – | 0.085 | −0.109 | −0.036 |
| Fluid Intelligence | | | | – | −0.175 | −0.002 |
| Age | | | | | – | 0.065 |

ICS, Isomer Creativity Score; AUT, Alternate Uses Task; DAT, Divergent Association Task. Gender is coded as 0 = female, 1 = male. * $p < 0.05$, ** $p < 0.01$, 2-tailed.

TABLE 3 Partial correlation coefficients (controlling for age, gender, and fluid intelligence) for ICS, AUT and DAT indices of creativity ($N = 104$).

| Measure | AUT Flexibility | AUT Creativity | DAT |
|---|---|---|---|
| ICS | 0.241* | 0.129 | 0.147 |

ICS, Isomer Creativity Score; AUT, Alternate Uses Task; DAT, Divergent Association Task. *$p < 0.017$, 2-tailed.

revealed a significant positive correlation between the ICS and AUT Flexibility. However, the correlations between ICS and (a) AUT Creativity and (b) DAT, were not statistically significant, although both were in the positive direction. These results indicate that individuals who demonstrated higher creativity in the chemistry task also tended to score higher on the AUT Flexibility, even when accounting for differences in age, gender, and fluid intelligence. In simple terms, this suggests that creative thinking skills in a specific scientific domain, like chemistry, are related to certain aspects of broader creative abilities, particularly those involving flexibility in divergent thinking.

## Discussion

The purpose of this study was twofold: First, to develop a new measure of creativity within the domain of organic chemistry (the DSFT) and, second, to examine the relationship between domain-specific creativity in chemistry, as measured by the DSFT, and more general measures of creativity, including the AUT and the DAT. Our findings revealed a significant positive correlation between DSFT and AUT flexibility scores, even when controlling for age, gender, and fluid intelligence. This suggests that the ability to generate diverse and flexible solutions in chemistry is related to broader creative thinking skills as measured by the AUT. Notably, however, no significant correlations were found between DSFT and AUT creativity or DAT scores, indicating that the relationship between domain-specific and domain-general creativity may be more nuanced and specific to the particular assessment of creativity employed.

While it is not entirely clear why AUT flexibility, but not AUT creativity or DAT scores, correlated with creative performance on the DSFT, we speculate that this outcome may be due to the nature of the cognitive processes involved in the different tasks. With respect to AUT Creativity, this measure focuses on the originality and novelty of responses, which may assist in generating isomers within a given set of related isomers. However, without the cognitive flexibility measured by AUT flexibility (which did correlate with ICS), participants may become constrained within a specific set of similar isomers, which could thereby lead to lower creativity on the DSFT. This suggests that the ability to shift cognitive sets, as indexed by AUT flexibility, may be crucial for producing a diverse range of isomers.

With respect to the DAT, the lack of significant correlation with DSFT performance may be due to the DAT's focus on verbal creativity. Indeed, the DAT measures the ability to generate semantically distant words, which involves verbal and linguistic skills. In contrast, the DSFT requires the generation of diverse chemical structures, a task that relies more on spatial and domain-specific knowledge rather than verbal creativity. Thus, the cognitive processes underpinning DAT performance may not align closely with those required for success on the DSFT, possibly explaining the non-significant correlation observed.

Alternatively, the lack of significant correlations may be attributable to our relatively small sample size: Both of the non-significant correlations were in the positive direction, suggesting that with a larger sample size (and, hence, greater statistical power), these correlations might reach statistical significance. While obtaining larger sample sizes in these studies is somewhat challenging—since data collection was limited to currently enrolled Organic Chemistry students at the same academic stage—future studies with a larger cohort might reveal significant correlations across all measures.

In any case, the results from this study suggests that, at least when it comes to divergent thinking as measured by the AUT flexibility (one of the most commonly employed indices of creativity in psychological literature), there is some overlap between domain-general and domain-specific creativity. Critically, this finding has important implications for the ongoing debate regarding domain-generality versus domain-specificity in creativity research (e.g., Chen et al., 2006; Baer, 2012). Indeed, it indicates that certain cognitive processes involved in creative thinking are applicable across different domains, supporting the domain-generality perspective. This means that strategies and interventions designed to enhance general creative thinking skills (particularly flexibility) could be beneficial across various fields, including highly specialized areas like organic chemistry. Moreover, this overlap suggests that our understanding of the correlates of general creative thinking can be extended to specialized fields. By applying what we know about the factors that enhance general creativity, we can better understand and foster creativity in specific disciplines, thereby promoting innovation and problem-solving within those fields.

On the other hand, the lack of significant correlations with other general measures of creativity suggests that the overlap between domain-general and domain-specific creativity is not universal across all general creativity measures. This indicates that the applicability of findings regarding domain-general creative thinking skills to specialized fields likely depends on the particular

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measure of general creativity being considered. This, in turn, implies a more nuanced conclusion in the domain generality/specificity debate: the evidence supporting either perspective varies depending on the specific measure employed. In the present case, cognitive flexibility, as measured by AUT Flexibility, is relevant to creative performance in organic chemistry. However, other aspects of creativity, such as those measured by AUT Creativity and DAT, may involve different cognitive processes that do not align as closely with the demands of domain-specific tasks. Thus, this highlights the importance of using multiple, targeted assessments to capture the full range of creative abilities across different contexts and domains.

Moving forward with research into creativity in STEM fields, the DSFT represents a significant advancement in measuring domain-specific creativity in chemistry. Unlike many traditional creativity assessments that rely on subjective ratings from multiple raters, the DSFT allows for the objective quantification of creativity in the domain of organic chemistry: By calculating the rarity of each response based on a comprehensive set of possible isomers, the DSFT provides an unbiased and precise measure of creative performance. Ultimately, the DSFT not only advances our understanding of creativity in chemistry, but also sets a precedent for developing similar domain-specific measures across other scientific disciplines, thereby fostering a more nuanced and comprehensive understanding of creative processes in STEM.

## Conclusions and considerations for teaching

Creativity measurements often draw on divergent tasks, in which there is not a single defined problem-solving pathway. Similarly, multiple pathways are often feasible for solving problems from general chemistry to graduate chemistry courses. Despite multiple pathways being feasible, because of larger class sizes, limited resources, and challenges with evaluating performance, assessments often focus on problems that have defined solutions and answers. While this is understandable given challenges, instructors could perhaps consider occasional opportunities to foster creativity through divergent tasks, which could include problem construction, in which students design problems, broader questions that require assumptions, estimation, or approximation with justification, and comparison and evaluation of syntheses and other problem-solving strategies. While we agree more research is needed to understand creativity in STEM, we hypothesize incorporating divergent activities will foster the development of creativity, which will enhance students' abilities to synthesize and extend on course concepts.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by Duke University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their electronic informed consent to participate in this study.

## Author contributions

CB: Funding acquisition, Visualization, Resources, Formal analysis, Validation, Project administration, Writing – original draft, Investigation, Supervision, Data curation, Writing – review & editing, Methodology, Software, Conceptualization. NB: Writing – original draft, Writing – review & editing. BM: Writing – original draft, Writing – review & editing, Formal analysis, Data curation. HH: Writing – review & editing, Writing – original draft. CC: Conceptualization, Writing – review & editing, Investigation, Formal analysis, Supervision, Resources, Data curation, Project administration. PS: Methodology, Investigation, Writing – review & editing, Conceptualization, Data curation, Validation, Writing – original draft, Resources, Formal analysis, Visualization, Supervision, Project administration, Funding acquisition.

## Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The Charles Lafitte Foundation Program for Research in Psychology and Neuroscience at Duke University.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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