Creative Research Journal

ISSN: 1040-0419 (Print) 1532-6934 (Online) Journal homepage: www.tandfonline.com/journals/hcrj20

Capturing Creative Imagination in the Adolescent Brain: Development of a Novel fMRI Task

Shulang Yue, Michaelle E. DiMaggio-Potter, Celia Durkin, Yuko Taniguchi, Zeynep Başgöze, Laura Padilla, Bryon A. Mueller, Donovan J. Roediger, Bonnie Klimes-Dougan, Kathryn R. Cullen & Wilma Koutstaal

To cite this article: Shulang Yue, Michaelle E. DiMaggio-Potter, Celia Durkin, Yuko Taniguchi, Zeynep Başgöze, Laura Padilla, Bryon A. Mueller, Donovan J. Roediger, Bonnie Klimes-Dougan, Kathryn R. Cullen & Wilma Koutstaal (03 Jul 2025): Capturing Creative Imagination in the Adolescent Brain: Development of a Novel fMRI Task, Creativity Research Journal, DOI: 10.1080/10400419.2025.2524347

To link to this article: https://doi.org/10.1080/10400419.2025.2524347

CREATIVITY RESEARCH JOURNAL
https://doi.org/10.1080/10400419.2025.2524347

Routledge
Taylor & Francis Group

Capturing Creative Imagination in the Adolescent Brain: Development of a Novel fMRI Task

Shulang Yue[a], Michaelle E. DiMaggio-Potter[a], Celia Durkin[a], Yuko Taniguchi[b], Zeynep Başgöze[a], Laura Padilla[a], Bryon A. Mueller[a], Donovan J. Roediger[a], Bonnie Klimes-Dougan[a], Kathryn R. Cullen[a], and Wilma Koutstaal[a]

[a]University of Minnesota Twin Cities; [b]University of Minnesota Rochester

ABSTRACT
Adolescence is a pivotal time for developing creative imagination. To advance knowledge about the neural underpinnings of creative imagination during this critical developmental phase, a task capable of eliciting meaningful creative imagination that could be used during functional magnetic neuroimaging (fMRI) in adolescents was designed with input from adolescents. The task shows a series of images (photographs) together with different verbal prompts to either mentally imagine something about or beyond what is seen in the image ("Imagine") or to mentally describe specific aspects of each image ("Describe"). Fourteen adolescents completed the fMRI procedure and provided feedback in the scanner and afterward. Whole brain activation analyses revealed that "Imagine" involved greater recruitment of several key regions within the default mode network than "Describe." In-scanner ratings indicated that participants actively engaged in the task and easily followed the instructions. Thematic analysis on participants' written recollections of their thoughts during "Imagine" identified various themes of creative imagination elicited by the task. Psycholinguistic comparisons showed that whereas thoughts during "Imagine" were characterized by greater authenticity, "Describe" showed more analytical thinking. The Imagination fMRI task is a novel tool that may be used to advance the study of creative imagination in the adolescent brain.

Introduction

Adolescence is a critical time for the development and cultivation of creativity (Kleibeuker, De Dreu, et al., 2013, Kleibeuker et al., 2016, Stevenson et al., 2014). Research has highlighted the importance of nurturing creativity in education for a broad array of student outcomes (Collard & Looney, 2014; Moreno & Del Mar Molero Jurado, 2023). The transitional phase between puberty and adulthood is a key period for the development of cognitive, emotional, and social skills and aptitudes, and deeply draws on these skills (Steinberg, 2005). This phase is considered a pivotal time of increasing exploration and autonomy (Spear, 2000), flexible thinking (Kleibeuker, De Dreu, et al., 2013; Stevenson et al., 2014), self-discovery and self-reflection (Dahl et al., 2018; Nurmi, 2004), as well as creative identity development (Barbot & Heuser, 2017; Beghetto & Dilley, 2016) and identity formation in general (Marcia, 1966; Meeus et al., 2010). All of these changes coincide with significant structural and functional changes in the brain during adolescence (Giedd et al., 1999; Luna et al., 2010; Sydnor et al., 2021). Advancing current understanding of how creative abilities and their underlying neural processes evolve across the adolescent period represents an important area of study that holds relevance for broad fields spanning education, neuroscience, health, arts, design, social sciences, and beyond. However, as we argue below, capturing neurocognitive changes in meaningful creative ideation during this transitional period poses a challenge that requires the development of new tools.

While creativity draws on multiple cognitive-perceptual processes including divergent thinking, imagination, inspiration, insight, design thinking, novel combination, reflection, and iteration (Kaufman & Beghetto, 2009; Koutstaal & Binks, 2015; Runco & Jaeger, 2012), much of the prior research on the neural mechanisms underlying creative processes has focused on divergent thinking. A common experimental paradigm to assess divergent thinking is the alternative uses task (AUT), in which participants are asked to think of unusual or atypical uses for an ordinary object. Past research using functional magnetic resonance imaging (fMRI) demonstrated that compared to young adults,

CONTACT Shulang Yue yuexx142@umn.edu Department of Psychology, University of Minnesota Twin Cities, 75 East River Road, Minneapolis, MN 55455, USA
Supplemental data for this article can be accessed online at https://doi.org/10.1080/10400419.2025.2524347

while performing the AUT, adolescents recruited the same overall network (i.e., regions involved in the default mode network [DMN] including left angular gyrus, left supramarginal gyrus, and bilateral middle temporal gyrus), although correlations between performance and prefrontal cortex activation were stronger in the adults (Kleibeuker, Koolschijn, et al., 2013). Notably, while divergent thinking is considered an indication of creative potential (Karwowski & Beghetto, 2019; Runco & Acar, 2012), it also represents just one (relatively narrow) aspect of creative thinking. However, other aspects of creative thinking are relatively less studied, especially in adolescents. In particular, creative imagination, defined as the ability to use mental images to create original ideas, stories, or narratives based on past observations or existing knowledge through a variety of association and combinatorial processes (Abraham, 2016; Glaveanu et al., 2017; Karwowski et al., 2022), may be critical to understand in adolescents. The processes underlying creative imagination include three interrelated elements: vividness (ability to produce mental imagery with a high level of detail), originality (ability to produce novel mental imagery), and transformativeness (ability to manipulate mental imagery) (Jankowska & Karwowski, 2015). Thus, from a broader, cognitive neuroscience perspective, creative imagination is more than just mental imagery, instead representing a multimodal constructive process that – depending on task demands and the scaffolding provided in the task stimuli and instructions – draws on both semantic and episodic processing, including abstract thoughts, inferences, and reflections (Andrews-Hanna & Grilli, 2021; Irish, 2020).

Recent work has begun to develop novel paradigms for examining the neural basis of creative imagination, typically with a focus on a particular content domain, such as scientific reasoning (e.g., Beaty et al., 2023) or visual creativity (e.g., Lloyd-Cox et al., 2021), or with a focus on a specific cognitive phenomenon, such as the detrimental constraining effects of a prior interpretation on creative and imaginative thoughts (e.g Frith et al., 2022). Across fMRI studies, tasks intended to invoke imagination have broadly demonstrated the recruitment of brain regions in the DMN (Andrews-Hanna & Grilli, 2021). However, limitations of existing fMRI tasks include the lack of personal relevance for participants, and a failure to offer substantial and evocative stimulation in a way that invites meaningful imaginative exploration. These factors introduce the potential for disengagement and boredom with the activity, especially for adolescents. For example, the widely used AUT has been criticized for lacking true novelty and for potentially invoking simply remembered responses rather than spontaneous and in-the-moment imaginative thinking. This is because the AUT often involves familiar and everyday objects that may not be personally meaningful, and participants may rely on their memories by recalling how they or others have used these objects in the past instead of actively engaging in creative generation of alternative uses (Gilhooly et al., 2007). Those memory-based responses are often perceived as less creative by both participants themselves and external judges (Benedek et al., 2018; Silvia et al., 2017). Also, while human imaginative and creative thinking engage both conceptual and perceptual processes (e.g., Abraham, 2016; Irish, 2020), the AUT places greater emphasis on the conceptual aspect of divergent thinking (Wu & Koutstaal, 2020), offering limited support for personally meaningful imaginative exploration. To our knowledge, this is the first study to develop an fMRI task explicitly tailored to assess creative imagination in adolescents.

Therefore, in the current study, a novel fMRI task was designed to capture brain activation particularly during *creative imagination* in adolescents. Specifically, the aim was to tap into a process that would feel meaningful, engaging, and enjoyable to adolescents. Thus, the development of this task involved a co-creation process with adolescents. In contrast to prior creative imagination research that focused on visual scenario construction or the cognitively fixating effects of a prior interpretation (e.g., Jankowska & Karwowski, 2015; Lloyd-Cox et al., 2021), here a more holistic approach was adopted – aiming to both support (scaffold) and invoke – meaningful and self-relevant imaginative thinking in adolescents. In addition to collecting the neuroimaging data, in-scanner ratings and post-scan questionnaires were also administered to assess participants' performance and experience with the novel task, as well as their recollections of their thoughts during the experiment. It was hypothesized that this fMRI-compatible paradigm would be capable of eliciting personally meaningful imaginative thinking in adolescents, and that it would invoke activation in brain regions typically associated with imagination and creative thinking (e.g., regions within the DMN) (Andrews-Hanna & Grilli, 2021; Shofty et al., 2022).

Method

Participants

Adolescents between the ages of 13–17 years were recruited to participate in a study that involved arts activities, co-creation of an fMRI task, and participating in fMRI scans. Participants were recruited from the local community with assistance from multiple institutes at the University of Minnesota. Exclusion criteria included

Table 1. Participant demographic information and characteristics for the fMRI sample.

Sample Characteristics (*N* = 14)	
Characteristic	*n* (%)
Age, mean (*SD*)[a]	17.3 years (1.2)
Race/Ethnicity	
Asian	1 (7.1)
Asian/White	2 (14.3)
Black	2 (14.3)
Black/White	1 (7.1)
Hispanic or Latinx	1 (7.1)
Native American/White	1 (7.1)
White	6 (42.9)
Sex at Birth	
Female	11 (78.6)
Male	3 (21.4)

[a]Participants' age assessed at the time of the fMRI scanning session.

MRI scan contraindications, a history of neurological illnesses that might confound MRI analyses, a history of moderate to severe neurodevelopmental disorders (e.g., autism or intellectual disorders), a health or behavioral condition that might interfere with participating safely in study activities (e.g., severe medical conditions that may impact an adolescent's ability to participate or exceedingly aggressive behavior/violent outbursts), unwillingness to participate in the proposed study activities, active suicidality without agreeing to a safety plan, and inability to speak English. All adolescents and their parents or guardians provided informed consent prior to any data collection or other participation, and the study was approved by the University of Minnesota Institutional Review Board (IRB: STUDY00015930). Participants were compensated with $50 per fMRI scan. Eight participants participated in the co-creation process of the fMRI task (described below), and fourteen participants completed the fMRI scanning. Table 1 provides the demographic data for the participants who participated in fMRI scanning. (Note: fMRI scanning occurred about 9 months after participants enrolled in the study; ages reported in the Table are from the time of the fMRI scanning session). More detailed demographic information can be found in Supplementary Materials B Table B.1.

Development of the imagination task

The Imagination task was created through a collaborative process involving scientists (including those with neuroimaging expertise and those with expertise in creativity science), artists, and co-created together with adolescent participants during several sessions of *Imagination Central*, a nine-month after-school creative arts and science program (Yue et al., 2025/in preparation). The task involved two main conditions – Imagine and Describe – both of which involved viewing images (photographs) depicting various natural or social scenes, presented together with an accompanying verbal (written and auditory) prompt. During the Imagine condition, participants were prompted to mentally imagine themselves within or beyond the presented context suggested by the image and the prompts. In particular, participants were prompted to "Vividly and deeply imagine yourself in the situation suggested by the image and the instructions. You don't have to follow the instructions exactly; you can create your own narrative inspired by the image." Thus, the prompt served as a starting point for creative imagination, and participants were invited to take their imagination in whatever direction they wished from that starting point. During the Describe condition, which serves as the control condition, participants viewed the same images, but the prompts instructed participants to mentally describe specific aspects of the images. Each image appeared twice – once with an Imagine prompt and once with a Describe prompt – to allow within-subject comparisons of the Imagine and Describe conditions while equating the visual stimuli. Figure 1 provides an example of the images and the accompanying written prompts for the Imagine versus Describe conditions. The examples are shown in the same format as they would be presented in the fMRI scanner.

The co-creation process with adolescents

During the *Imagination Central* program, adolescents had opportunities to practice and hone their creativity through engaging in creative arts and reflection (Yue et al., 2025/in preparation). While most of the sessions centrally involved creative arts activities, three sessions had a scientific focus. During one of the science sessions, a parallel prototyping approach (i.e., receiving feedback on multiple prototypes in parallel; Dow et al., 2010) was implemented in which adolescents worked together to first experience and then discuss their experiences with early versions of the Imagine and Describe prompts. In this session, the prompts were presented in one of the three sensory modalities (i.e., written-only, auditory-only, and auditory + written prompts) and the content of the prompts was either generic or explicitly tied to each of the images (i.e., image-specific vs. non-image-specific). The image stimuli used in this parallel prototyping session were sourced from the website https://burst.shopify.com/, and were freely available for use without any copyright restrictions. The images were composed of photographs featuring a wide range of categories, including animals, people, architecture, geographical formations, writing and art-related materials, among others. Feedback was solicited from the adolescents regarding which sensory modality (or modalities) was most optimal for their

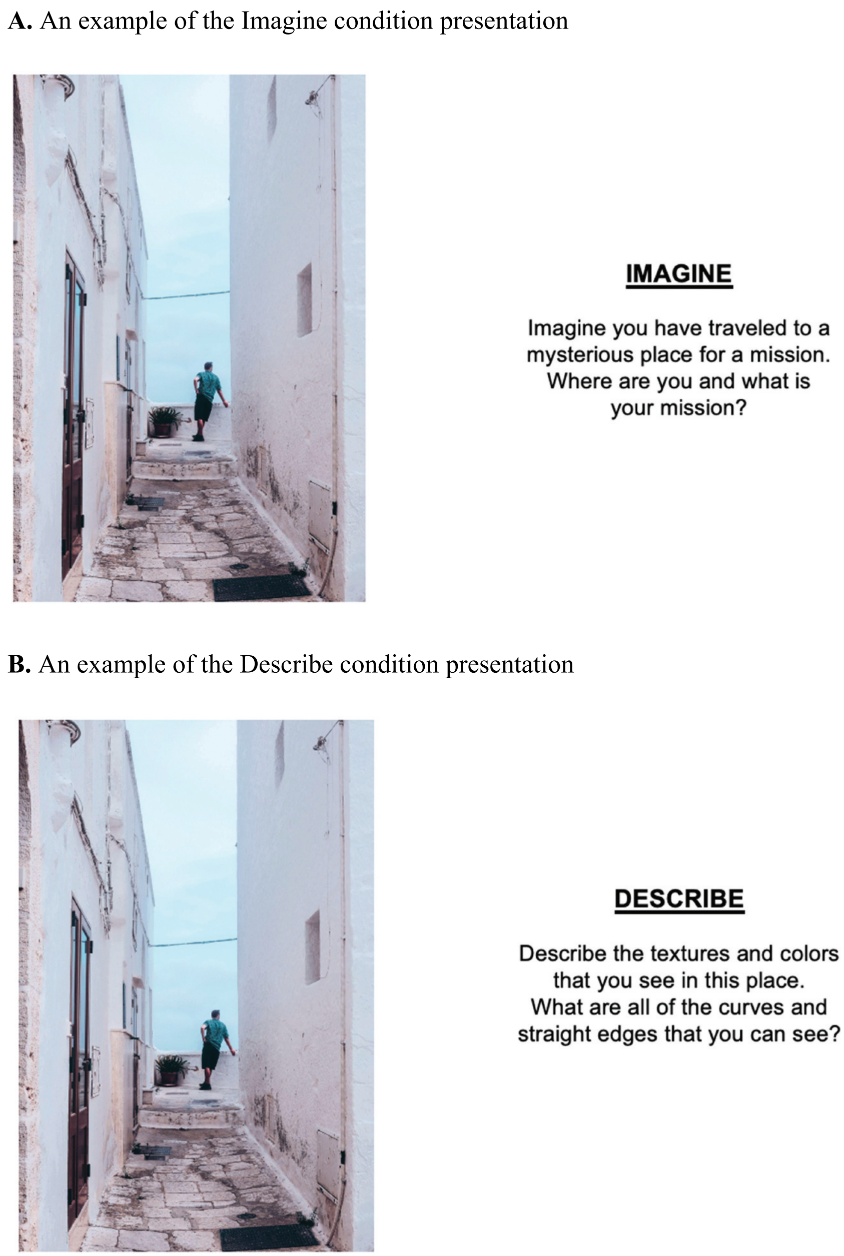

Figure 1. Examples of imagine and describe conditions. For illustrative purposes and to protect the novelty of the stimuli, the example image and the prompts are taken from the pre-scanner practice session (described below).

creative imagination, and whether they preferred the prompts to be more directive and specific to each image versus less directive and more general/common across images.

To ensure both the Imagine and Describe conditions of the task were engaging enough, yet not too difficult (i.e., in terms of generating ideas) for adolescents, we recorded a subgroup of participants' ($n = 8$) feedback via survey and descriptively analyzed their feedback to guide our design of the actual stimuli. Results indicated that participants enjoyed the set of stimuli presented as both auditory + written prompts the most and found image-specific prompts to be easier to respond to, compared to non-image-specific prompts. As a result, the final stimuli for both the Imagine and Describe conditions included pairs of written and auditory (spoken) prompts (with the same wording), recorded by one researcher from the team. This combined visual and spoken format was adopted to enhance adolescents' experience and provide enough scaffolding (rich and evocative stimulation) to increase the likelihood of facilitating more imaginative involvement and engagement in the scanner. Additionally, based on the adolescents' feedback, the final stimuli were chosen to be image-specific rather than generic across all stimuli.

Designing the imagine and describe stimuli

A collection of 73 entirely new visual images for the participants was identified and selected, ensuring there was no overlap in the stimuli presented during the parallel prototyping session. These images were selected by the same research team members from the same website https://burst.shopify.com/, without strict copyright limitations, covering the same range of image categories as the early versions used in the parallel prototyping session.

To accompany each of the images, under the direction of the scientist and artist leads, several undergraduate and graduate students helped develop a set of varied and engaging verbal prompts. Since the aim was to elicit personally meaningful and highly salient creative ideas, the Imagine prompts were specifically designed to invite adolescents to imagine what they would do, feel, or think if they were in a particular situation, emphasizing an inner-directed generative activity. Conversely, the Describe prompts were designed with a focus on outer-directed and externally-guided activity. All Imagine and Describe prompts were directive and tailored to each image, and were written in an inclusive and open-ended way with the goal of inviting imaginative and descriptive responses.

Following the selection of images and the creation of written prompts, the team iteratively refined the stimuli based on seven key constraints:

(1) The images and verbal prompts should evoke generally positive feelings, aligning with the goal of tapping into enjoyable creative thinking.
(2) The images must exclude any text within them. This constraint aimed to eliminate attentional competition with the written prompt, ensure optimal visibility of the images, and enhance future accessibility of the stimuli and the task across languages.
(3) The length of the verbal prompts needed to approximately match across all images, maintaining similarity across task conditions and stimuli.
(4) All verbal prompts followed a specific structure, comprising a statement followed by relevant questions to guide the participants' imagination or description.
(5) The statements in the Imagine prompts always began with the word "Imagine," while the Describe prompts started with "Describe."
(6) The number of questions included in the prompts for the Imagine and Describe conditions were also equated within each image.
(7) The Imagine and Describe prompts for each image included the same referent word denoting a central focus in the stimulus image (e.g., cat, lighthouse, dancer).

After implementing these constraints, feedback was sought from other team members to ensure that the images and the verbal prompts were appropriate, clear, and contextually suitable for adolescents, incorporating their input in an iterative manner to further refine the images and prompts. After arriving at a refined set of 39 stimuli, the task was piloted (outside the scanner) with a team of twelve undergraduate and graduate students to finalize decisions on the timing and the inclusion of the stimuli. For these students, the average length of time spent thinking about each stimulus was 24.7 seconds. Therefore, the duration of the stimuli for the scanner-based task was set to 25 seconds. Using a 5-point scale, students rated the extent to which they were able to, for the Imagine condition, vividly or deeply imagine, or, for the Describe condition, clearly or fully describe, each image. These ratings were used to exclude stimuli with an average rating below 3.5, resulting in the elimination of 4 stimuli. Moreover, the prompts underwent refinement based on the written feedback received from the students. Since only 24 stimuli were needed given our fMRI task design (described below), we additionally eliminated 3 stimuli and assigned 8 stimuli to the pre-scanner practice session (described below) while ensuring a roughly equal representation of each image category (e.g., people, animals, architecture, reading, travel, etc.).[1] After several cycles of iterations and refinements, the stimuli for the task were finalized. The full set of stimuli, including images, verbal prompts, audio-recordings, and the pre-scanner practice materials can be found in Supplementary Materials A. Summary characteristics of the stimuli, including the number of questions and number of words in the prompts, and the duration of auditory presentation, can be found in Supplementary Materials B Table B.2.

Designing the fMRI experiment

For two distinct purposes, two fMRI-compatible versions of this paradigm were developed: 1) the Interleaved version was optimized for conventional fMRI analyses of brain activation (e.g., contrasting brain activation in the Imagine versus Describe conditions), and 2) the Continuous version was designed for analyses that require longer lengths of continuous data that is collected during a given context, such as measuring entropy of the fMRI signal, or carrying out dynamic functional connectivity analysis. Both task versions consisted of two runs, each featuring a different set of stimuli. Stimuli were assigned to the different versions (Interleaved, Continuous) and runs (run 1, run 2) to ensure an approximate even distribution of image categories. The current paper focuses on the results obtained using the Interleaved task version, measuring brain activation at the whole-brain level, with one exception, noted later in the Post-scan survey analysis section.

In the Interleaved task version, the order of the Imagine and Describe conditions was counterbalanced in two different sequences as two different blocks for each run: one block as IDDI and another block as DIID (I: Imagine, D: Describe), with the purpose of having a more robust estimation of the scanner drift (Dale & Buckner, 1997) and minimizing any differential effects of scanner drift across the two conditions. The visual images and written prompts remained on the screen the entire time of each trial (i.e., 25 seconds) while participants were contemplating their responses to each stimulus. A 6-second rest period was interposed between each trial, during which participants were instructed to look at a fixation cross. To provide additional data that could be used as a "baseline," in addition to the 6-second rest periods between trials, each run included a 25-second rest period (fixation cross) at the beginning and the end of the IDDI and DIID blocks. Moreover, to obtain within-scanner assessments of participants' performance, but without repeatedly encouraging evaluative thinking, at the end of each 4-trial block, participants rated (via button-box press) how vividly or deeply they imagined, and how clearly or fully they were able to mentally describe the images on a 3-point rating scale (1 = not at all, 2 = somewhat, 3 = quite well) (see Figure 2). Each run begins with 46 seconds of rest time during which the scanner undergoes calibration (required for the multiband acquisition), and in each run, the Imagination task lasted 6 minutes and 47 seconds (231 volumes) and included 4 images, each presented twice, in different blocks, once as Imagine and once as Describe. Participants completed two runs of the Interleaved task version with four different images in each run. Table B.3 in Supplementary Materials B provides detailed experimental timing information. Design information regarding the Continuous task version is also reported in Supplementary Materials B.

Counterbalancing

To allow for counterbalancing, four task variations of each of the two task versions, Interleaved and Continuous, were created and administered (see Supplementary Materials B Table B.4), with two different orders of stimulus presentation in each run, and two different options of run order (run 1 first, run 2 second, or the opposite) for each task version. Additionally, approximately half of the participants completed the Interleaved version first and the other half completed it second (see Supplementary Materials B Figure B.2 for counterbalancing method illustration). In other words, all participants viewed the same set of stimuli, but the stimuli presentation order varied depending on the counterbalancing condition to which participants were assigned.

Data collection: scanning procedure

Scanning was completed at the Masonic Institute for the Developing Brain at the University of Minnesota. Upon arrival, participants completed a screen to ensure safety for entering the MRI suite. Adolescents then completed a pre-scanner practice session with additional stimuli (four for each task version) presented on a desktop computer to become acquainted with the task and to understand the instructions (see Supplementary Materials A for the pre-scanner practice materials). They were also given the opportunity to try out a mock scanner, to become more familiar with the scanning environment. Participants were then brought to the Siemens 3T Prisma whole body MRI scanner. A 32 channel head coil was used. The Siemens auto align head sequence was used to prescribe all scans to improve within and between session reproducibility. Structural T1/T2 weighted data were acquired using the ABCD acquisition (1 mm isotropic, etc.). For all functional data (resting state scans and Imagination task), the multi-echo fMRI sequence was used with the following parameters: repetition time 1761 ms, echo times 14.20/38.93/63.93/88.39 ms, voxel size 2 mm isotropic, a multiband factor of 6, and IPAT factor of 2. A pair of opposite phase-encoded multi-echo spin echo field maps were acquired with voxel parameters matched to the fMRI data for use in distortion correction. A resting-state fMRI scan (12 minutes/410 volumes) was also collected, which is not the focus of this work.

After completing each fMRI scanning session, all participants were asked to complete a questionnaire about their experiences with the procedure. The questions addressed their comfort, alertness, and nervousness levels inside the scanner as well as how hard or easy it was to follow the task instructions (i.e., verbal prompts) and to shift their attentional focus for each image. Furthermore, participants were shown each picture with the accompanying verbal prompt and were asked to rate each stimulus on three distinct dimensions: the effectiveness of the image and the

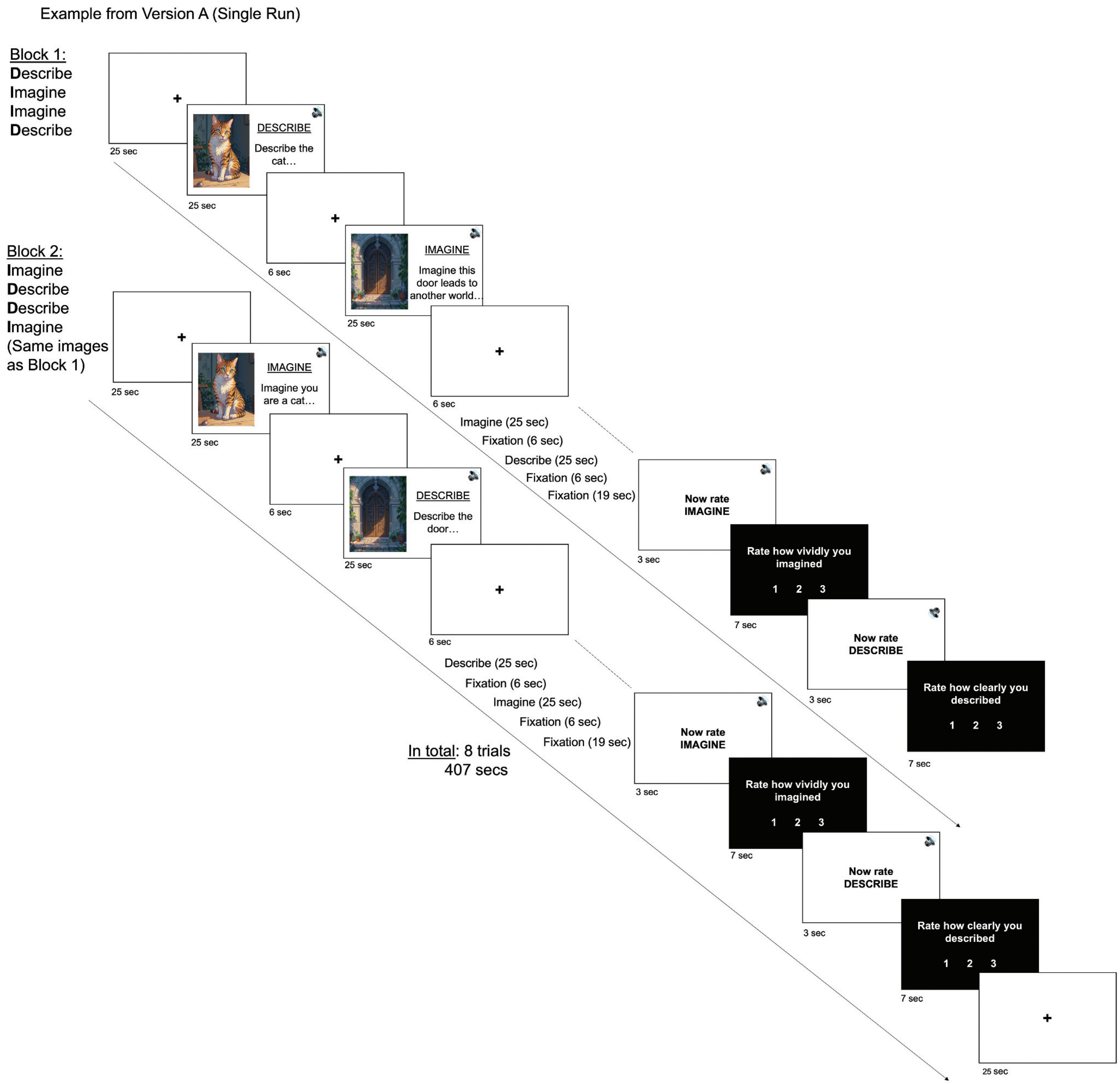

Figure 2. Experiment flow of the interleaved version for a single run. Participants rated how vividly or deeply they imagined and how clearly or fully they were able to mentally describe the images on a 3-point rating scale (1 = not at all, 2 = somewhat, 3 = quite well) at the end of each block. The images in this flowchart are simplified and cartoon versions of the actual stimuli, re-created on getting.ai (https://getimg.ai/), for illustrative purposes and to protect the novelty of the stimuli. The full images and the accompanying verbal prompts for the Interleaved task version can be found in Supplementary Materials A.

accompanying verbal prompts, the amount of time they spent imagining/describing the stimulus, and their level of enjoyment while engaging with the stimulus as much as they could remember. Participants were then again shown all the images and the corresponding verbal prompts in a single array, and were asked to select two of their favorite images. They were asked to write down what they remembered they had imagined and described for those two images during the scanning session. This provided a way to both inform the research team about the kinds of ideas that were generated during the task, and also the extent to which different images were liked by different participants. Such information about all of the prompts would have been useful; however, adolescents were asked to respond in detail only about two of the images, in order to minimize their task load and to provide them with increased autonomy regarding what they would choose to reveal.

MR data processing

DICOM data were converted to the Brain Imaging Data Structure (BIDS) standard format. Raw MRI data underwent NORDIC denoising (version 1.1; Vizioli et al., 2021) and were then preprocessed using fMRIprep (version 24.0.0; Esteban et al., 2018). These steps included coregistration and normalization to MNI volume space for both T1w and T2w images and motion correction, distortion correction, T2*-weighted optimal combination of echoes using Tedana (version 24.0.1; DuPre et al., 2021), and registration to MNI space for the BOLD data.

fMRI data analysis

The current study focuses on the analyses conducted on the Interleaved version of the task, to measure brain activation at the whole-brain level. All analyses were performed in MNI volume space. Motion confounds using the six canonical motion regressors were extracted from fMRIprep and input into the first-level analyses, with no censoring applied for high motion frames. First-level analyses were performed for each run using Python's Nilearn (version 11.1; Abraham et al., 2014), regressing the task model against the whole-brain fMRI data, to obtain whole-brain beta-maps for the following contrasts: Imagine > Describe, Describe > Imagine, Imagine > Fixation, and Describe > Fixation. Then, within-session beta maps for the two runs were averaged for each contrast. Group-level inference was performed using a one-sample *t*-test, with beta values tested against zero, resulting in a whole-group beta map for each contrast. Multiple comparisons were corrected using permutation testing with cluster-mass error control. In this procedure, a cluster-forming threshold of $p < .001$ was used to select clusters. These clusters were tested against a null distribution of cluster masses. The null distribution was estimated by randomly drawing locations of coordinates from a gray matter template and recording the maximum cluster mass, repeated with 10,000 iterations; *p*-values were obtained for each cluster, and clusters that survived the $p < .05$ are displayed on the whole group beta maps for each contrast.

Post-scan survey analysis

Summary statistics on the quantitative results of the surveys were conducted. To better understand and characterize the kinds of creative imagination our task was eliciting, we looked at participants' free-written responses regarding their "favorite" stimuli to identify themes of creative imagination. In addition, Linguistic Inquiry Word Count (LIWC) (using LIWC-22; Boyd et al., 2022; Pennebaker et al., 2015) was used to analyze their free-written responses. Note that to ensure a sufficient amount of text and findings based on a sufficient number of stimuli that were selected by participants as their "favorite" (a total of 16 across the two task versions), both the thematic analysis identifying instances of creative imagination and the LIWC analyses included qualitative data from both task versions. The LIWC application first counts all the words in a target text and then calculates the percentage of total words that belong to each of several categories. The application also provides summary values on four more complex and integrative dimensions (called "summary variables"), which are rescaled so that they are on a 100-point scale ranging from 0 to 100. The four LIWC summary variables are:

(1) Analytic thinking – higher values indicate more formal or logical thinking, whereas a lower number is indicative of more informal, personal, or narrative thinking.
(2) Clout – higher values indicate speaking from a position of relatively greater expertise or authority, whereas lower values indicate a more tentative or unassuming style.
(3) Authentic – higher values are reflective of responses that are more personal, honest, and disclosing, whereas lower numbers indicate more guarded or distanced responding.
(4) Tone – higher values are indicative of a more positive, upbeat emotional tone, whereas lower numbers may reflect negative states such as anxiety, sadness, or hostility.

In addition to these summary variables, results from six LIWC psychological categories were examined: motivational drives (e.g., affiliation, achievement, power), cognition (e.g., insight, memory), affect (e.g., positive emotion, negative emotion), social processes and referents (e.g., conflict, friends, family), perception (including space), and time.

To address our hypothesis that the Imagination task would be capable of eliciting personally meaningful imaginative thinking in adolescents, we compared the following LIWC variables in the responses to the Imagine prompts versus responses to the Describe prompts: socioemotional and self-related words, Authenticity, Positive Tone, and Analytic summary measures. Results regarding each of these psycholinguistic domains of interest listed above were averaged for each of the 16 selected "favorite" stimuli for Imagine versus Describe.

Results

Neuroimaging results

Whole-brain contrasts for the imagine > describe and describe > imagine conditions

Whole brain activation analyses were conducted to compare brain activity between the Imagine and Describe conditions. After correcting for multiple comparisons with permutation testing, the contrast of Imagine > Describe yielded significant activation in the left lateral occipital cortex, which was notably accompanied by activation in the posterior cingulate gyrus and several more anterior (and transmodal) regions, including the left middle temporal gyrus – anterior division, left temporal pole, and frontal pole (see Table 2 and Figure 3). The direct contrast of Describe > Imagine revealed extensive activation in bilateral visual processing regions, including especially the right lateral occipital cortex – superior division and left occipital pole (see Table 2 and Figure 3).

Table 2. Significant clusters from the whole-brain one-sample analysis for the imagine > describe and describe > imagine contrasts.

Region Name	Cluster ID	X	Y	Z	Peak Stat (*t*-score)	Cluster Size (Cubic mm)
Imagine > Describe						
Middle temporal gyrus - anterior division (left)	1	−58.5	−6.5	−20.5	2.70	8240
Lateral occipital cortex - superior division (left)	2	−46.5	−68.5	39.5	1.80	3656
Posterior cingulate gyrus (medial)	3	−8.5	−52.5	29.5	1.80	3528
Temporal pole (left)	4	−49.5	7.5	−26.5	1.80	3240
Superior frontal gyrus (medial)	5	−2.5	51.5	35.5	1.66	2104
Frontal pole (medial)	6	−8.5	57.5	−2.5	1.11	960
Describe > Imagine						
Lateral occipital cortex - superior division (right)	1	15.5	−76.5	57.5	4.02	4032
Occipital pole (left)	2	−34.5	−92.5	3.5	2.88	4456
Lateral occipital cortex - superior division (right)	3	31.5	−86.5	21.5	2.76	6392

All coordinates are in the MNI volume space. The X, Y, and Z values for the coordinates of the peak are in millimeters.

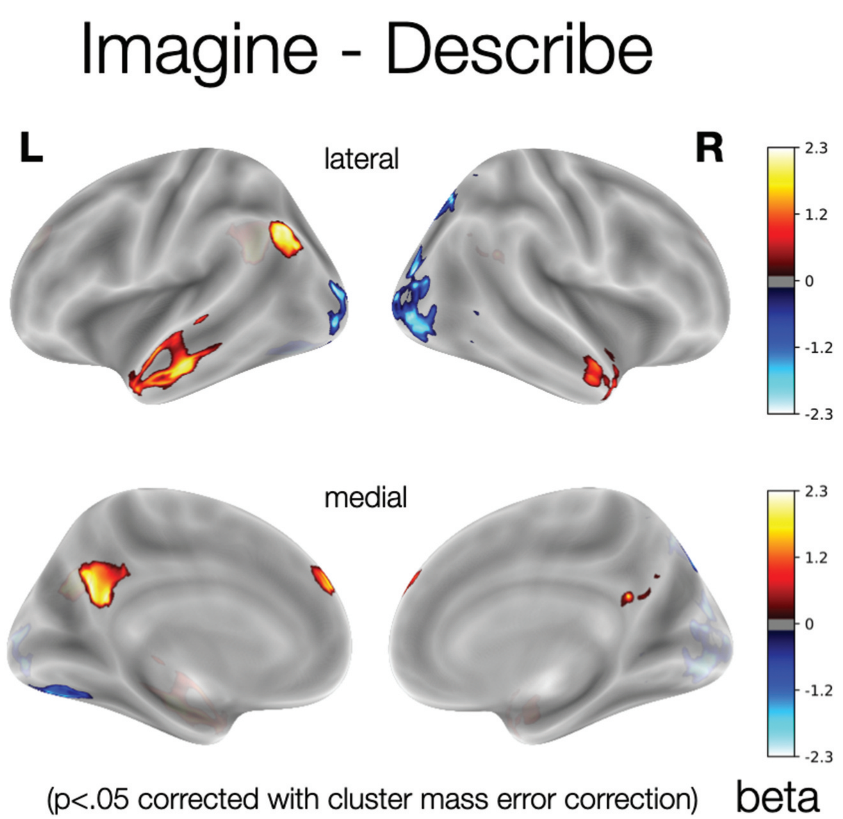

Figure 3. Significant clusters from the whole-brain one-sample analysis for the imagine > describe (warm colors) and the describe > imagine contrasts (cool colors). Beta values for voxels with $p < .05$ (corrected based on the distribution of maximum cluster masses from 10,000 permutations). Warmer colors (red to yellow) indicate brain regions that were relatively more activated during the Imagine than the Describe condition; cooler colors (dark to light blue) indicate brain regions that were more activated during the Describe than the Imagine condition.

Table 3. Significant clusters from the whole-brain one-sample analysis for the imagine > fixation and describe > fixation contrasts.

Region Name	Cluster ID	X	Y	Z	Peak Stat (*t*-score)	Cluster Size (Cubic mm)
Imagine > Fixation						
Occipital fusiform gyrus (right)	1	27.5	−80.5	−18.5	11.57	66432
Middle temporal gyrus - anterior division (left)	2	−64.5	−8.5	−8.5	4.47	12488
Angular gyrus (left)	3	−44.5	−58.5	25.5	2.95	2216
Superior temporal gyrus - anterior division (right)	4	63.5	−4.5	−8.5	2.95	3232
Inferior frontal gyrus - pars opercularis (left)	5	−56.5	19.5	15.5	1.85	1336
Describe > Fixation						
Occipital fusiform gyrus (right)	1	29.5	−80.5	−18.5	14.76	104344
Superior temporal gyrus - posterior division (left)	2	−60.5	−38.5	3.5	3.55	6872
Planum temporale (right)	3	55.5	−14.5	5.5	3.20	2776

All coordinates are in the MNI volume space. The X, Y, and Z values for the coordinates of the peak are in millimeters.

Whole-brain contrasts for the imagine > fixation and describe > fixation conditions

As shown in Table 3 and Figure 4, the contrast of Imagine against Fixation revealed significant clusters in the right occipital fusiform gyrus, left middle temporal gyrus – anterior division, left angular gyrus, the right superior temporal gyrus – anterior division, and left inferior frontal gyrus – pars opercularis. The contrast of Describe against Fixation yielded three peaks, including the right occipital fusiform gyrus, left superior temporal gyrus – posterior division, and right planum temporale.

Behavioral results

In-scanner rating

Across both the Imagine and Describe conditions, participants reported strong success in engaging in the Interleaved task: Mean = 2.446, 95% CI [2.243, 2.650] on the 3-point scales. Participants also reported highly similar levels of success in engaging in the Imagine and Describe tasks: Mean Imagine = 2.482, 95% CI [2.214, 2.750], Mean Describe = 2.411, 95% CI [2.078, 2.744]. Across 112 in-scanner ratings for the Interleaved version (14 participants with 8 ratings per participant), there were only 7 occasions where participants reported ratings of 1 (indicating inability or difficulty completing the designated task for a stimulus block), with these ratings occurring relatively less often for Imagine (2 times) than for Describe (5 times). Figure 5 illustrates the distribution of the average in-scanner ratings in the Interleaved version. The behavioral results for the Continuous version are reported in Supplementary Materials B.

Post-scan survey

While 35.7% of participants reported being more alert for the first run compared to the second, most participants reported similar alertness across runs. Regarding participants' experiences of seeing each image twice with different instructions (i.e., once with Imagine instructions, and once with Describe instructions), 71% of respondents answered it was "very easy" or "easy" and no respondents indicated that it was either

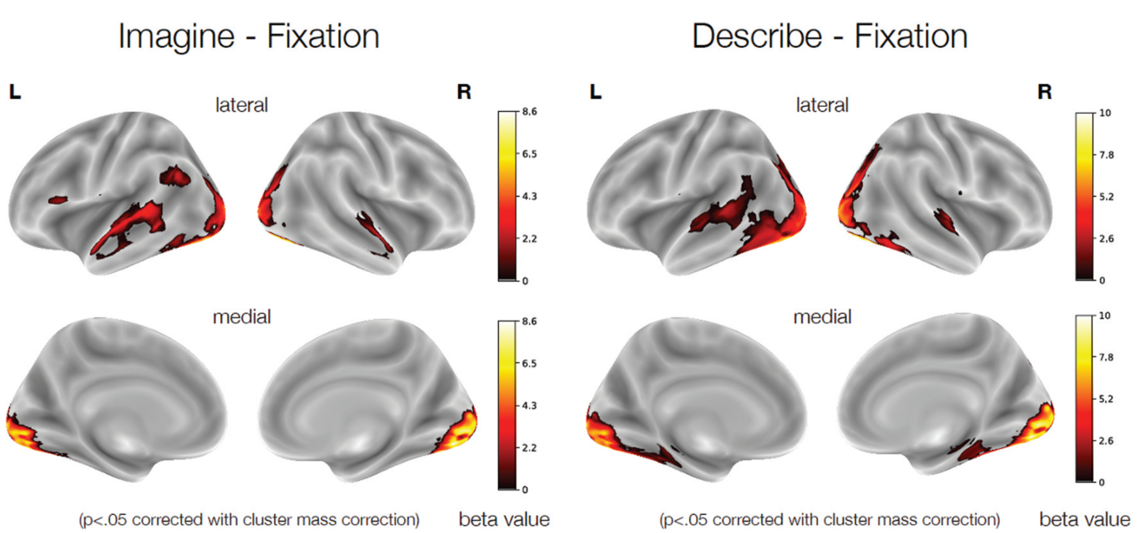

Figure 4. Significant clusters from the whole-brain one-sample analysis for the imagine > fixation and describe > fixation contrasts. Beta values for voxels with $p < .05$ (corrected based on the distribution of maximum cluster masses from 10,000 permutations). The maximum beta value for the Imagine > Fixation contrast is 8.6 and for the Describe > Fixation contrast is 10.

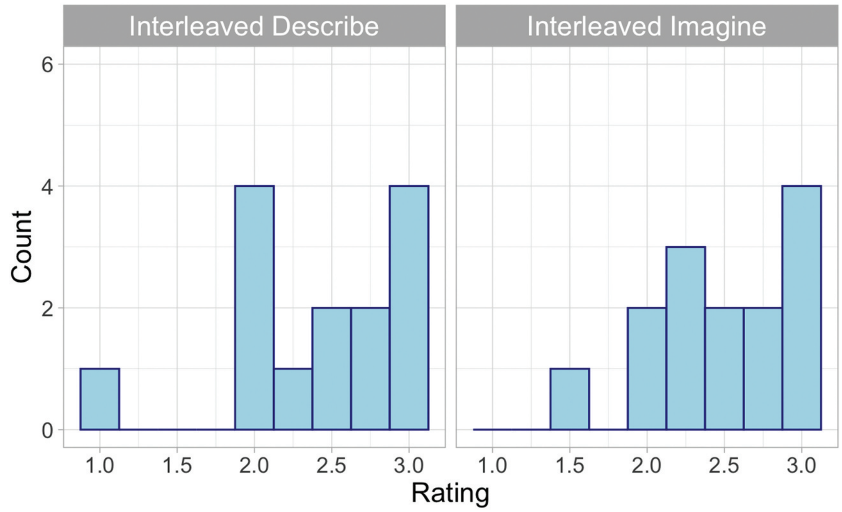

Figure 5. Histograms of average in-scanner ratings for the interleaved version. Participants responded (via button-box press) on a scale of 1–3 how vividly or deeply they felt they were able to imagine (Imagine condition), or how clearly or fully they were able to mentally describe (Describe condition) for the immediately prior subset of 4 stimuli.

"hard" or "very hard" to shift their focus. In addition, most participants reported that it was not confusing to see each image twice with different instructions. Particularly, no participants responded that it was either "confusing" or "very confusing." For the Interleaved runs, which required more frequent shifts, 86% of the adolescents noted it was "not at all confusing" or "not confusing." All participants reported that it was "somewhat helpful" to "very helpful" to see each image twice with different instructions (i.e., imagine or describe).

Moreover, 11 out of 16 Interleaved stimuli (68.9%; combining Imagine and Describe) were reported as enjoyable (i.e., "I really enjoyed imagining/describing this image and prompt") by more than half of the participants. Averaging across all the Interleaved stimuli participants had encountered, the majority of participants reported using the entire provided time (i.e., 25 seconds) to mentally respond, both for the Imagine stimuli ($M = 11.25$) and the Describe stimuli ($M = 9.75$). Most participants also indicated that they enjoyed engaging with both the Imagine stimuli ($M = 9.88$) and the Describe stimuli ($M = 8.50$) (see Supplementary Materials B Figure B.3).

Descriptive themes of creative imagination

Across both task versions, there were a total of 16 different visual stimuli selected by the participants as a "favorite," and for which one or more participants provided a post-scan characterization of their recalled thoughts during both the Imagine prompts and the Describe prompts. We identified several descriptive themes of creative imagination by focusing on their responses to the Imagine prompts in both task versions to characterize distinct aspects of creative imagination that were evoked by the task. Table 4 presents the five themes that we identified along with some illustrative examples. All of the adolescents' qualitative responses are provided in Supplementary Materials B Table B.7.

Psycholinguistic analysis of thoughts during imagine and describe

Similarly, participants' qualitative responses from both task versions were included in the LIWC analyses to ensure a sufficient amount of text and generalizability across stimuli. As shown in Table 5, the psycholinguistic characteristics of these descriptions differed in several ways for the Imagine versus Describe conditions. Compared to the reports for the Describe trials, reports for the Imagine trials were longer, had significantly higher levels of Authenticity and Positive Tone, contained significantly more references to motivational drives, cognition, and affect, and included a higher proportion of references to time. In contrast, reports of thoughts during the Describe condition were characterized by a significantly higher level of Analytic language.

Discussion

The current study presents a novel task designed to capture brain functioning during meaningful imagination in adolescents that was developed through a co-creation process involving artists, scientists, and adolescent participants. Our preliminary results indicated that adolescents found the task to be well tolerated, enjoyable, easy for switching their focus between the Imagine and Describe trials, and capable of eliciting meaningful,

Table 4. Descriptive themes of creative imagination identified from the qualitative responses with illustrative examples for each theme.

Theme	Illustrative Examples
Personification and transformation	• "I imagined the treasure being a cat that talks and grants wishes when you pet its tail." • "I imagined that a mermaid came to see me. Because it's a mermaid it turned me into one too, and we explored the ocean."
Imaginative empathic projection and conceptual expansion	• "I was thinking about the ocean itself being my friend. It was bringing me shells and such and I'd help its animals get better taking care of them until they're ready to go back." • "I was thinking about how the bird would tell me how successful I will become in life and how I need to keep doing what I'm doing and how I'm strong and amazing."
Narrative immersion and unfolding quest/questioning	• "You're out on the water on your boat when you find a cave that you've never seen before, it's as if it had appeared out of nowhere. You go inside and find a treasure chest full of old coins, bones, pearl necklaces, and gold but at the bottom is a scroll, it's in a foreign language and you can't understand. All of a sudden you notice that some of the symbols look familiar, where have you seen these from before?" • "That one of the trees contained rubber ducks but they weren't ordinary rubber ducks, they were magical rubber ducks and if you took one, it would make one thing about you perfect. However, if you took more than you were allowed you would start to have a big ego and others would start to see you as less perfect the more ducks you take."
Magical travel in time and space	• "While imagining, I thought about the door transporting me to China, or wherever in the world I would want to go to. In China, I imagined I would see my family, see the ocean, and eat good food." • "I imagined a crow found me when flying home and noticed that I looked lost. I imagined him swooping in from the right of me to get my attention. I then knew to follow him, and I did until he took me back to the main road."
Playful, metaphorical thinking and humor/storytelling	• "I imagined I was a lemon, sour and unpleasant but with the right things, I can be very nice to have around."

Table 5. The means for the LIWC measures, and the results of repeated measures ANOVAs comparing the means (per stimulus) for imagine and describe.

LIWC Measure	Imagine Mean (*SD*)	Describe Mean (*SD*)	Imagine vs. Describe
Word Count[a]	28.73 (12.29)	17.01 (10.71)	$F(1, 14) = 13.80$, $p = .002$**
Analytic	44.08 (19.13)	72.50 (24.07)	$F(1, 15) = 9.20$, $p = .008$**
Clout	15.02 (21.07)	23.09 (13.44)	$F(1, 15) = 2.55$, $p = .13$
Authentic	89.21 (11.33)	45.59 (31.87)	$F(1, 15) = 43.70$, $p < .001$***
(Positive) Tone	49.00 (27.56)	30.30 (16.46)	$F(1, 15) = 4.63$, $p = .048$*
Drives[a]	3.28 (3.27)	0.00 (0.0)	$F(1, 14) = 15.04$, $p = .002$**
Cognition	15.77 (6.21)	6.25 (5.50)	$F(1, 15) = 37.20$, $p < .001$***
Affect[a]	5.15 (3.81)	0.85 (1.11)	$F(1, 14) = 14.06$, $p = .002$**
Social	9.55 (6.51)	7.57 (5.10)	$F(1, 15) = 2.00$, $p = .18$
Perception	10.92 (7.80)	10.29 (6.52)	$F(1, 15) = 0.05$, $p = .83$
Space	5.09 (3.65)	5.35 (3.99)	$F(1, 15) = 0.07$, $p = .80$
Time[a]	4.32 (2.83)	1.15 (1.48)	$F(1, 14) = 10.78$, $p = .005$**

LIWC, Linguistic Inquiry Word Count; [a]Excluding one outlier value for the analysis. For statistically significant comparisons, the shaded cell indicates the condition with a higher value.

authentic, and positively valenced thoughts. The task also evoked different aspects of creative imagination. Preliminary results from the group analysis of the fMRI data suggested that the task elicited activation in brain regions that are typically associated with imagination and creative thinking reported in prior research. The unique collaboration undertaken in this research allowed some key innovations including the ability to tap a creative and imaginative process that is not typically captured in previous creative imagination research, which is illustrated in the content of thinking shared by adolescent participants after the scan.

The behavioral results suggested that the novel Imagination task paradigm successfully encouraged participants to actively engage in the tasks and appropriately follow the different instructions provided. These results showing that the Imagine and Describe conditions elicited similar levels of *in-situ* self-assessed successful task performance support the validity of comparing the neuroimaging data between the Imagine and Describe conditions. Across all scanning sessions, there were only two occasions where participants did not respond to the rating activity (or did not respond within the time limit provided), suggesting that the pacing for rating was reasonable. In addition, given that participants reported the same level of alertness for the two scan runs in the post-scan survey, it appears feasible to administer two runs on a given day in the manner adopted in this study for participants of this age group. Post-scan survey results further suggested that participants enjoyed the selected images and the accompanying verbal prompts, and 25-seconds as the duration of the stimuli was appropriate.

By identifying descriptive themes of creative imagination from adolescents' written summaries of their thoughts during the Imagination task, we were able to show how the Imagination task captured different aspects of creative imagination, ranging from personification and transformation to magical travel in time and space, that are personally relevant to participants. The psycholinguistic results of the adolescents' qualitative responses revealed significant differences between Imagine and Describe conditions for the LIWC indices of Authenticity, Positive Tone, Motivational Drives, Cognition, and Affect. Notably, higher levels of Authenticity in the Imagine condition align with our intention in designing the Imagine prompts to evoke personally meaningful thinking, making each participant's responses individually meaningful and authentic to themselves. Thus, even though the actual content and the direction of participants' imaginative explorations clearly and markedly differed from one another, as shown, for instance, in the illustrated responses in Table 4, the psycholinguistic data underscore their genuine and inventive engagement with the prompts. However, it should be noted that Positive Tone was only slightly higher in the Imagine trials compared to the Describe trials. Nevertheless, the significant difference between the two conditions in Affect could support and cohere with the subtle difference in Positive Tone. In contrast, the high level of Analytic language in the Describe trials also implied that the Describe condition served as a good contrast and control task to the Imagine condition. Overall, the preliminary behavioral findings suggest that the Imagination task is capable of eliciting authentic, positive, playful, and self-reflective imaginative thoughts, contrasted with analytical thoughts, in adolescents inside the scanner, placing it uniquely from other commonly used fMRI tasks, such as the AUT, that typically do not involve personal relevance and do not provide evocative stimulation that allows personally meaningful imaginative exploration.

The neuroimaging analysis results showed that, as hypothesized, compared to the Describe condition, the Imagine condition elicited greater activation in several regions that are part of the DMN. Specifically, the middle temporal gyrus plays an important role in both the semantic and default mode networks (Cogdell-Brooke et al., 2020). This region is associated with the construction of new associations and concepts when processing novelty and usefulness in creativity (Ren et al., 2020), reflecting the association and combination processes of creative imagination. The posterior cingulate cortex and superior frontal gyrus are also key hubs within the DMN (Fernandino & Binder, 2024; Raichle et al., 2001). Our preliminary findings are in line with prior studies that implicated the DMN in "mental time travel" (i.e., when engaging in imagining the future or recalling the past), tasks that require semantic processing and memory retrieval (Smallwood et al., 2021), and visual creativity (Zhu et al., 2017). Moreover, the peak of the frontal pole activation observed in the current study was largely medial and appeared close to a core anterior medial prefrontal hub of the DMN (Andrews-Hanna et al., 2010; Wen et al., 2020). This activation was also near the region that is thought to be involved in guiding "attention and behavior related to linking stimuli to values and emotions" under the organizational framework of the frontal pole proposed by Orr et al. (2015). The proposed role of the region is highly congruent with the study's attempt to generate Imagine prompts that invited personally meaningful reflection and imaginative exploration by the adolescents. Furthermore, bilateral visual processing regions, including the occipital cortex – superior division, were observed in both conditions. Whereas the Imagine condition recruited relatively more left-lateralized activity in the occipital cortex, the Describe condition elicited more right-lateralized activity in this region. This right-lateralized activity was found to be involved in the local processing of object-based hierarchical stimuli (G. R. Fink et al., 1997; Kéïta & Bedoin, 2011), reflecting participants' efforts in describing the specific aspects of the images as prompted. In contrast, the left-lateralized activity was linked to the global processing of object-based stimuli, suggesting that participants used the holistic essence of the images to guide their creative imagination rather than focusing on the details of the images.

In addition to the direct contrasts of the Imagine and Describe conditions, a comparison of each condition against Fixation could help to further reveal similarities and differences between the Imagine and Describe conditions given that the potential cognitive contributors to the two conditions may be varied and complex. Contrasts of the Imagine and Describe conditions against Fixation both revealed an extensive activation in the right occipital fusiform gyrus, presumably reflecting the combined visual images and visual written prompts presented for both conditions and absent during fixation. However, the two conditions differed in that the Describe trials (relative to low-level fixation) but not the Imagine trials activated language-related processing in the right planum temporale, potentially reflecting increased stimulus-driven attention to the auditory spoken prompt during the Describe trials (Hirnstein et al., 2013). Additionally, the Imagine trials (relative to low-level fixation) but not the Describe trials called on more semantic/transmodal/language/meaning-related processing in the left angular gyrus (e.g., Seghier, 2023) and left inferior frontal gyrus – pars opercularis, regions related to increased conscious inner speech, narration, or self-talk (Amit et al., 2017).

The Imagine trials also elicited greater activation in the right superior temporal gyrus, an area associated with semantic integration and perhaps reflective of the inferences participants made when transitioning from the presented verbal prompt to their own imaginative construction (e.g., Gündüz et al., 2020; Mason & Just, 2004; Virtue et al., 2006).

The findings of the current study are also consistent with several prior fMRI studies on divergent thinking, creative problem-solving, and imagination. For example, Kleibeuker, Koolschijn, et al. (2013) found that both adolescent and adult participants displayed increased activations in the left angular gyrus and bilateral middle temporal gyrus during AUT trials in comparison to the AUT control condition, the object characteristics (OC) task, where participants are asked to generate characteristics of common objects. Similarly, by contrasting the AUT versus the OC task, A. Fink et al. (2010) reported stronger activation in the left angular gyrus, while we observed activation in this area when contrasting Imagine with Fixation. When contrasting AUT with Fixation, A. Fink et al. (2009) observed greater activation in the inferior frontal gyrus (left) which we also found in the Imagine > Fixation contrast. Although our task recruited similar key regions as reported by past studies using the AUT and OC task, what differentiates our contrast between the Imagine versus Describe conditions from the typical contrast between the AUT and the OC task is that our contrast is a stronger comparison between externally-focused thought (Describe) versus internally-focused thought (Imagine) with both conceptual and perceptual processing, whereas the contrast for the AUT versus the OC task is more strongly a comparison between two forms of internally-generated thought (i.e., creative and imaginative simulation for the AUT versus semantic, conceptual, and perceptual memory retrieval for the OC task). Furthermore, inferior frontal gyrus, middle temporal gyrus, and superior occipital gyrus were also found to be recruited during creative problem-solving using the Matchstick problem task in adolescents (Kleibeuker, Koolschijn, et al., 2013). In a more recent study, Shofty et al. (2022) confirmed the causal relationship between the default network node (i.e., posterior cingulate cortex) and divergent thinking. In addition, the posterior cingulate cortex, along with some other regions within the salience and semantic control networks, were identified during scientific creative imagination (Beaty et al., 2023), suggesting a commonality of brain region recruitment across different types of creative cognition. Likewise, the inferior and middle temporal gyri were found to be engaged in creative imagery, crucial for recognizing and categorizing meaningful visual inputs, and together with the superior occipital gyrus, they synergistically facilitated the mental representation of visual-spatial characteristics (Frith et al., 2022). Notably, the significant voxel clusters identified in the study included brain regions that were proposed to be associated with both the mental imagery and semantic features of imaginative thought (Andrews-Hanna & Grilli, 2021). Specifically, the medial temporal lobe, the posterior cingulate cortex, and the inferior parietal lobe are closely associated with the mental imagery aspect of imagination, while the dorsal medial prefrontal cortex, the temporoparietal junction, and the temporal pole are associated with the semantic processing of imaginative thought (Andrews-Hanna et al., 2014).

Limitations and future directions

One limitation of the study is the small sample size ($N = 14$) which contributed to lower power to detect significant effects, so the current results should be considered preliminary. Future research will benefit from larger sample sizes, a goal we hope will be facilitated through our sharing of all the Imagination task stimuli here (see Supplementary Materials A). A second limitation pertained to the analysis of thought content, in which we relied on participants' retrospective recall of thoughts during the scan. However, potential drawbacks/limitations of a retrospective reporting procedure were mitigated by eliciting the participants' reports soon after they completed the scans and also while providing strong retrieval support by showing the participants the images and the verbal prompts again. Future studies may benefit from adopting a strategy where participants are instructed to think aloud during creative imagination – ideally during a form of neuroimaging acquisition that is not strongly adversely influenced by head motion (but see Li et al., 2023). This approach would capture participants' imaginative thinking in real-time, allowing researchers to better understand the dynamic properties of imaginative thought, which could ultimately lead to deeper insights into various imaginative states (Andrews-Hanna & Grilli, 2021). Particularly, it is ideal for recording continuous streams of thought through written or spoken responses using the "think aloud" strategy (D'Argembeau & Mathy, 2011).

A third limitation – that is, however, also a notable strength – is the multifaceted, varied, and complex nature of the combined visual and verbal stimuli provided in the Imagination task. On the one hand, the rich and varied stimuli were iteratively generated so as to both support – and invite – meaningfully creative imaginative constructions by adolescent youth in the (often less than fully facilitative) context of fMRI scanning, with all of its accompanying constraints on sensory and motor activity. The complexity of the stimuli aligns with the complexity of imaginative operations in our everyday lives, and with emerging conceptual analyses of the varied mental imagery, recollective, prospective, and combinational or generative processing that are part and parcel of what is known as "imagination" (Abraham, 2016; Andrews-Hanna & Grilli, 2021; Irish, 2020). On the other hand, to nonetheless allow experimental control and valid comparisons, the complexity was countered by presenting the same visual stimuli (for the same duration) in both the Imagine and Describe conditions, and by equating the general format and specificity of the accompanying verbal prompts. That differences in cognitive and neural processing (BOLD activation) were observed during the Imagine trials (predominantly involving internally-directed attention) versus Describe trials (predominantly involving externally-directed attention), even with continuously present and equated complex images, offers the opportunity for new explorations of differential network connectivity during internally- versus externally-oriented conscious processing (cf. Dixon et al., 2014; Lyu et al., 2021). Neural connectivity and other analyses may further inform understanding of how the default mode network dynamically interfaces with other large-scale networks to enable the vast reaches of human creative imagination.

Conclusion

We present a novel Imagination fMRI task that captures brain activation during creative imagination in adolescents. This Imagination task is unique among other creative imagination tasks in that it was developed specifically with adolescents in mind and through an active and extended co-creation process with adolescents themselves. The preliminary findings suggest that this task is capable of eliciting various aspects of creative imaginative thinking that are self-reflective, meaningful, and positive in adolescents as well as invoking brain activations in several key regions within the default mode network that are typically associated with imagination and creative thinking. The current report and accompanying supplementary materials aim to make this new investigative paradigm accessible to other researchers, thereby facilitating the exploration and study of the neurobiological underpinnings of self-reflective and meaningful imaginative thinking across various contexts. This task could be useful in research designed to examine change across adolescent development, as a result of experimental interventions, or in relation to the introduction of socio-cultural and educational programs that aim to foster, and extend, the creative – and imaginative – use of imagination.

Note

1. Given the high average (and low standard deviation) of ratings ($M = 4.08$, $SD = 0.25$) from the pilot data across the final set of the stimuli, and given the relatively small number of stimuli that we had to choose from, we prioritized the even distribution of image categories across task versions and runs (see the Designing the fMRI experiment section).

Acknowledgments

We wish to especially thank the adolescents who participated in the *Imagination Central* study, and their families who supported their participation. We would also like to thank the undergraduate and graduate students who contributed to the development and piloting of the verbal prompts. Finally, we extend our deep gratitude to Dr. Angus MacDonald III and Dr. Amy Kuceyeski for their valuable advice on the fMRI task design.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Endowment for the Arts [Research Lab Grant 1891865-38-22]; the Biotechnology Research Center [Grant No. P41EB015894]; the National Institute of Neurological Disorders & Stroke Institutional Center Core Grants to Support Neuroscience Research [Grant No. P30NS076408]; and the High-Performance Connectome Upgrade for Human 3T MR Scanner [Grant No. 1S10OD017974] (for the infrastructure to collect data); computational support was provided by the Minnesota Supercomputing Institute.

References

Abraham, A. (2016). The imaginative mind. *Human Brain Mapping*, *37*(11), 4197–4211. https://doi.org/10.1002/hbm.23300

Abraham, A., Pedregosa, F., Eickenberg, M., Gervais, P., Mueller, A., Kossaifi, J., Gramfort, A., Thirion, B., & Varoquaux, G. (2014). Machine learning for neuroimaging with scikit-learn. *Frontiers in Neuroinformatics*, *8*, 14. https://doi.org/10.3389/fninf.2014.00014

Amit, E., Hoeflin, C., Hamzah, N., & Fedorenko, E. (2017). An asymmetrical relationship between verbal and visual thinking: Converging evidence from behavior and fMRI. *NeuroImage*, *152*, 619–627. https://doi.org/10.1016/j.neuroimage.2017.03.029

Andrews-Hanna, J. R., & Grilli, M. D. (2021). Mapping the imaginative mind: Charting new paths forward. *Current Directions in Psychological Science*, *30*(1), 82–89. https://doi.org/10.1177/0963721420980753

Andrews-Hanna, J. R., Reidler, J. S., Sepulcre, J., Poulin, R., & Buckner, R. L. (2010). Functional-anatomic fractionation of the brain's default network. *Neuron*, *65*(4), 550–562. https://doi.org/10.1016/j.neuron.2010.02.005

Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: Component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, *1316*(1), 29–52. https://doi.org/10.1111/nyas.12360

Barbot, B., & Heuser, B. (2017). Creativity and identity formation in adolescence: A developmental perspective. In M. Karwowski & J. C. Kaufman (Eds.), *The creative self: Effect of beliefs, self-efficacy, mindset, and identity* (pp. 87–98). Elsevier Academic Press. https://doi.org/10.1016/B978-0-12-809790-8.00005-4

Beaty, R. E., Cortes, R. A., Merseal, H. M., Hardiman, M. M., & Green, A. E. (2023). Brain networks supporting scientific creative thinking. *Psychology of Aesthetics, Creativity, and the Arts*. https://doi.org/10.1037/aca0000603

Beghetto, R. A., & Dilley, A. E. (2016). Creative aspirations or pipe dreams? Toward understanding creative mortification in children and adolescents. *New Directions for Child and Adolescent Development*, *2016*(151), 85–95. https://doi.org/10.1002/cad.20150

Benedek, M., Schües, T., Beaty, R. E., Jauk, E., Koschutnig, K., Fink, A., & Neubauer, A. C. (2018). To create or to recall original ideas: Brain processes associated with the imagination of novel object uses. *Cortex, a Journal Devoted to the Study of the Nervous System and Behavior*, *99*, 93–102. https://doi.org/10.1016/j.cortex.2017.10.024

Boyd, R. L., Ashokkumar, A., Seraj, S., & Pennebaker, J. W. (2022). *The development and psychometric properties of LIWC-22*. University of Texas at Austin. https://www.liwc.app

Cogdell-Brooke, L. S., Sowden, P. T., Violante, I. R., & Thompson, H. E. (2020). A meta-analysis of functional magnetic resonance imaging studies of divergent thinking using activation likelihood estimation. *Human Brain Mapping*, *41*(17), 5057–5077. https://doi.org/10.1002/hbm.25170

Collard, P., & Looney, J. (2014). Nurturing creativity in education. *European Journal of Education*, *49*(3), 348–364. https://doi.org/10.1111/ejed.12090

Dahl, R. E., Allen, N. B., Wilbrecht, L., & Suleiman, A. B. (2018). Importance of investing in adolescence from a developmental science perspective. *Nature*, *554*(7693), 441–450. https://doi.org/10.1038/nature25770

Dale, A. M., & Buckner, R. L. (1997). Selective averaging of rapidly presented individual trials using fMRI. *Human Brain Mapping*, *5*(5), 329–340. https://doi.org/10.1002/(SICI)1097-0193(1997)5:5<329::AID-HBM1>3.0.CO;2-5

D'Argembeau, A., & Mathy, A. (2011). Tracking the construction of episodic future thoughts. *Journal of Experimental Psychology: General*, *140*(2), 258–271. https://doi.org/10.1037/a0022581

Dixon, M. L., Fox, K. C., & Christoff, K. (2014). A framework for understanding the relationship between externally and internally directed cognition. *Neuropsychologia*, *62*, 321–330. https://doi.org/10.1016/j.neuropsychologia.2014.05.024

Dow, S. P., Glassco, A., Kass, J., Schwarz, M., Schwartz, D. L., & Klemmer, S. R. (2010). Parallel prototyping leads to better design results, more divergence, and increased self-efficacy. *ACM Transactions on computer-Human Interaction*, *17*(4), 1–24. https://doi.org/10.1145/1879831.1879836

DuPre, E., Salo, T., Ahmed, Z., Bandettini, P., Bottenhorn, K., Caballero-Gaudes, C., Dowdle, L., Gonzalez-Castillo, J., Heunis, S., Kundu, P., Laird, A., Markello, R., Markiewicz, C., Moia, S., Staden, I., Teves, J., Uruñuela, E., Vaziri-Pashkam, M., Whitaker, K., & Handwerker, D. (2021). TE-dependent analysis of multi-echo fMRI with tedana. *Journal of Open Source Software*, *6*(66), 3669. https://doi.org/10.21105/joss.03669

Esteban, O., Markiewicz, C. J., Blair, R. W., Moodie, C. A., Isik, A. I., Erramuzpe, A., Kent, J. D., Goncalves, M., DuPre, E., Snyder, M., Oya, H., Ghosh, S. S., Wright, J., Durnez, J., Poldrack, R. A., & Gorgolewski, K. J. (2018). fMRIPrep: A robust preprocessing pipeline for functional MRI. *Nature Methods*, *16*(1), 111–116. https://doi.org/10.1038/s41592-018-0235-4

Fernandino, L., & Binder, J. R. (2024). How does the "default mode" network contribute to semantic cognition? *Brain and Language*, *252*, 105405. https://doi.org/10.1016/j.bandl.2024.105405

Fink, A., Grabner, R. H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., Neuper, C., Ebner, F., & Neubauer, A. C. (2009). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping*, *30*(3), 734–748. https://doi.org/10.1002/hbm.20538

Fink, A., Grabner, R. H., Gebauer, D., Reishofer, G., Koschutnig, K., & Ebner, F. (2010). Enhancing creativity by means of cognitive stimulation: Evidence from an fMRI study. *NeuroImage*, *52*(4), 1687–1695. https://doi.org/10.1016/j.neuroimage.2010.05.072

Fink, G. R., Marshall, J. C., Halligan, P. W., Frith, C. D., Frackowiak, R. S., & Dolan, R. J. (1997). Hemispheric specialization for global and local processing: The effect of stimulus category. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, *264*(1381), 487–494. https://doi.org/10.1098/rspb.1997.0070

Frith, E., Gerver, C. R., Benedek, M., Christensen, A. P., & Beaty, R. E. (2022). Neural representations of conceptual fixation during creative imagination. *Creativity Research Journal*, *34*(1), 106–122. https://doi.org/10.1080/10400419.2021.2008699

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., Paus, T., Evans, A. C., & Rapoport, J. L. (1999). Brain development during childhood and adolescence: A longitudinal MRI study. *Nature Neuroscience*, *2*(10), 861–863. https://doi.org/10.1038/13158

Gilhooly, K. J., Fioratou, E., Anthony, S. H., & Wynn, V. (2007). Divergent thinking: Strategies and executive involvement in generating novel uses for familiar objects. *British Journal of Psychology*, *98*(4), 611–625. https://doi.org/10.1111/j.2044-8295.2007.tb00467.x

Glaveanu, V. P., Karwowski, M., Jankowska, D. M., & de Saint Laurent, C. (2017). Creative imagination. In T. Zittoun & V. Glaveanu (Eds.), *The Oxford handbook of imagination* *and culture* (pp. 61–86). Oxford Academic. https://doi.org/10.1093/oso/9780190468712.003.0004

Gündüz, H., Baran, Z., Kır, Y., Sedes Baskak, N., & Baskak, B. (2020). Investigation of the cortical activity during episodic future thinking in schizophrenia: A functional near-infrared spectroscopy study. *Behavioral Neuroscience*, *134*(4), 344–357. https://doi.org/10.1037/bne0000377

Hirnstein, M., Westerhausen, R., & Hugdahl, K. (2013). The right planum temporale is involved in stimulus-driven, auditory attention - Evidence from transcranial magnetic stimulation. *PLoS ONE*, *8*(2), e57316. https://doi.org/10.1371/journal.pone.0057316

Irish, M. (2020). On the interaction between episodic and semantic representations - Constructing a unified account of imagination. In A. Abraham (Ed.), *The Cambridge handbook of the imagination* (pp. 447–465). Cambridge University Press. https://doi.org/10.1017/9781108580298.027

Jankowska, D. M., & Karwowski, M. (2015). Measuring creative imagery abilities. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.01591

Karwowski, M., & Beghetto, R. A. (2019). Creative behavior as agentic action. *Psychology of Aesthetics Creativity and the Arts*, *13*(4), 402–415. https://doi.org/10.1037/aca0000190

Karwowski, M., Zielińska, A., & Jankowska, D. M. (2022). Democratizing creativity by enhancing imagery and agency: A review and meta-analysis. *Review of Research in Education*, *46*(1), 229–263. https://doi.org/10.3102/0091732X221084337

Kaufman, J. C., & Beghetto, R. A. (2009). Beyond big and little: The four c model of creativity. *Review of General Psychology*, *13*(1), 1–12. https://doi.org/10.1037/a0013688

Kéïta, L., & Bedoin, N. (2011). Hemispheric asymmetries in hierarchical stimulus processing are modulated by stimulus categories and their predictability. *Laterality: Asymmetries of Body, Brain and Cognition*, *16*(3), 333–355. https://doi.org/10.1080/13576501003671603

Kleibeuker, S. W., De Dreu, C. K., & Crone, E. A. (2016). Creativity development in adolescence: Insight from behavior, brain, and training studies. *New Directions for Child and Adolescent Development*, *2016*(151), 73–84. https://doi.org/10.1002/cad.20148

Kleibeuker, S. W., De Dreu, C. K. W., & Crone, E. A. (2013). The development of creative cognition across adolescence: Distinct trajectories for insight and divergent thinking. *Developmental Science*, *16*(1), 2–12. https://doi.org/10.1111/j.1467-7687.2012.01176.x

Kleibeuker, S. W., Koolschijn, P. C. M., Jolles, D. D., Schel, M. A., De Dreu, C. K., & Crone, E. A. (2013). Prefrontal cortex involvement in creative problem solving in middle adolescence and adulthood. *Developmental Cognitive Neuroscience*, *5*, 197–206. https://doi.org/10.1016/j.dcn.2013.03.003

Kleibeuker, S. W., Koolschijn, P. C. M. P., Jolles, D. D., De Dreu, C. K. W., & Crone, E. A. (2013). The neural coding of creative idea generation across adolescence and early adulthood. *Frontiers in Human Neuroscience*, *7*. https://doi.org/10.3389/fnhum.2013.00905

Koutstaal, W., & Binks, J. (2015). *Innovating minds: Rethinking creativity to inspire change*. Oxford University Press.

Li, H. X., Lu, B., Wang, Y. W., Li, X. Y., Chen, X., & Yan, C. G. (2023). Neural representations of self-generated thought during think-aloud fMRI. *NeuroImage*, *265*, 119775. https://doi.org/10.1016/j.neuroimage.2022.119775

Lloyd-Cox, J., Christensen, A. P., Silvia, P. J., & Beaty, R. E. (2021). Seeing outside the box: Salient associations disrupt visual idea generation. *Psychology of Aesthetics, Creativity, and the Arts*, *15*(4), 575–583. https://doi.org/10.1037/aca0000371

Luna, B., Padmanabhan, A., & O'Hearn, K. (2010). What has fMRI told us about the development of cognitive control through adolescence? *Brain and Cognition*, *72*(1), 101–113. https://doi.org/10.1016/j.bandc.2009.08.005

Lyu, D., Pappas, I., Menon, D. K., & Stamatakis, E. A. (2021). A precuneal causal loop mediates external and internal information integration in the human brain. *Journal of Neuroscience*, *41*(48), 9944–9956. https://doi.org/10.1523/JNEUROSCI.0647-21.2021

Marcia, J. E. (1966). Development and validation of ego-identity status. *Journal of Personality and Social Psychology*, *3*(5), 551–558. https://doi.org/10.1037/h0023281

Mason, R. A., & Just, M. A. (2004). How the brain processes causal inferences in text: A theoretical account of generation and integration component processes utilizing both cerebral hemispheres. *Psychological Science*, *15*(1), 1–7. https://doi.org/10.1111/j.0963-7214.2004.01501001.x

Meeus, W., Van De Schoot, R., Keijsers, L., Schwartz, S. J., & Branje, S. (2010). On the progression and stability of adolescent identity formation: A five-wave longitudinal study in early-to-middle and middle-to-late adolescence. *Child Development*, *81*(5), 1565–1581. https://doi.org/10.1111/j.1467-8624.2010.01492.x

Moreno, A. G., & Del Mar Molero Jurado, M. (2023). Creativity as a positive factor in the adolescence stage: Relations with academic performance, stress and self-esteem. *Behavioral Sciences*, *13*(12), 997. https://doi.org/10.3390/bs13120997

Nurmi, J.-E. (2004). Socialization and self-development: Channeling, selection, adjustment, and reflection. In R. M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 85–124). John Wiley & Sons, Inc. https://doi.org/10.1002/9780471726746.ch4

Orr, J.M., Smolker, H. R., & Banish, M. T. (2015). Organization of the human frontal pole revealed by large-scale DTI-based connectivity: Implications for control of behavior. *PLoS ONE*, *10*(5), e0124797. https://doi.org/10.1371/journal.pone.0124797

Pennebaker, J. W., Boyd, R. L., Jordan, K., & Blackburn, K. (2015). *The development and psychometric properties of LIWC2015*. University of Texas at Austin. http://hdl.handle.net/2152/31333

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences*, *98*(2), 676–682. https://doi.org/10.1073/pnas.98.2.676

Ren, J., Huang, F., Zhou, Y., Zhuang, L., Xu, J., Gao, C., Qin, S., & Luo, J. (2020). The function of the hippocampus and middle temporal gyrus in forming new associations and concepts during the processing of novelty and usefulness features in creative designs. *NeuroImage*, *214*, 116751. https://doi.org/10.1016/j.neuroimage.2020.116751

Runco, M. A., & Acar, S. (2012). Divergent thinking as an indicator of creative potential. *Creativity Research Journal*, *24*(1), 66–75. https://doi.org/10.1080/10400419.2012.652929

Runco, M. A., & Jaeger, G. J. (2012). The standard definition of creativity. *Creativity Research Journal*, *24*(1), 92–96. https://doi.org/10.1080/10400419.2012.650092

Seghier, M. L. (2023). Multiple functions of the angular gyrus at high temporal resolution. *Brain Structure and Function*, *228*(1), 7–46. https://doi.org/10.1007/s00429-022-02512-y

Shofty, B., Gonen, T., Bergmann, E., Mayseless, N., Korn, A., Shamay-Tsoory, S., Grossman, R., Jalon, I., Kahn, I., & Ram, Z. (2022). The default network is causally linked to creative thinking. *Molecular Psychiatry*, *27*(3), 1848–1854. https://doi.org/10.1038/s41380-021-01403-8

Silvia, P. J., Nusbaum, E. C., & Beaty, R. E. (2017). Old or new? Evaluating the old/new scoring method for divergent thinking tasks. *The Journal of Creative Behavior*, *51*(3), 216–224. https://doi.org/10.1002/jocb.101

Smallwood, J., Turnbull, A., Wang, H., Ho, N. S. P., Poerio, G. L., Karapanagiotidis, T., Konu, D., Mckeown, B., Zhang, M., Murphy, C., Vatansever, D., Bzdok, D., Konishi, M., Leech, R., Seli, P., Schooler, J. W., Bernhardt, B., Margulies, D. S., & Jefferies, E. (2021). The neural correlates of ongoing conscious thought. *Iscience*, *24*(3), 102132. https://doi.org/10.1016/j.isci.2021.102132

Spear, L. P. (2000). The adolescent brain and age-related behavioral manifestations. *Neuroscience and Biobehavioral Reviews*, *24*(4), 417–463. https://doi.org/10.1016/s0149-7634(00)00014-2

Steinberg, L. (2005). Cognitive and affective development in adolescence. *Trends in Cognitive Sciences*, *9*(2), 69–74. https://doi.org/10.1016/j.tics.2004.12.005

Stevenson, C. E., Kleibeuker, S. W., de Dreu, C. K. W., & Crone, E. A. (2014). Training creative cognition: Adolescence as a flexible period for improving creativity. *Frontiers in Human Neuroscience*, *8*, 827. https://doi.org/10.3389/fnhum.2014.00827

Sydnor, V. J., Larsen, B., Bassett, D. S., Alexander-Bloch, A., Fair, D. A., Liston, C., Mackey, A. P., Milham, M. P., Pines, A., Roalf, D. R., Seidlitz, J., Xu, T., Raznahan, A., & Satterthwaite, T. D. (2021). Neurodevelopment of the association cortices: Patterns, mechanisms, and implications for psychopathology. *Neuron*, *109*(18), 2820–2846. https://doi.org/10.1016/j.neuron.2021.06.016

Virtue, S., Haberman, J., Clancy, Z., Parrish, T., & Jung Beeman, M. (2006). Neural activity of inferences during story comprehension. *Brain Research*, *1084*(1), 104–114. https://doi.org/10.1016/j.brainres.2006.02.053

Vizioli, L., Moeller, S., Dowdle, L., Akçakaya, M., De Martino, F., Yacoub, E., & Uğurbil, K. (2021). Lowering the thermal noise barrier in functional brain mapping with magnetic resonance imaging. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-021-25431-8

Wen, T., Mitchell, D. J., & Duncan, J. (2020). The functional convergence and heterogeneity of social, episodic, and self-referential thought in the default mode network. *Cerebral Cortex*, *30*(11), 5915–5929. https://doi.org/10.1093/cercor/bhaa166

Wu, Y., & Koutstaal, W (2020). Charting the contributions of cognitive flexibility to creativity: Self-guided transitions as a process-based index of creativity-related adaptivity. *PLoS ONE*, *15*(6), e0234473. https://doi.org/10.1371/journal.pone.0234473

Yue, S., DiMaggio-Potter, M. E., Taniguchi, Y., Wu, P., Molleti, S., Fiecas, M., Medina, A. M., Bernstein, G. A., Klimes-Dougan, B., Koutstaal, W., & Cullen, K. R. (2025). *Imagination central: An exploratory study of socio-cognitive processes of creativity in adolescents* [Manuscript in preparation]. Department of Psychology, University of Minnesota Twin Cities.

Zhu, W., Chen, Q., Xia, L., Beaty, R. E., Yang, W., Tian, F., Sun, J., Cao, G., Zhang, Q., Chen, X., & Qiu, J. (2017). Common and distinct brain networks underlying verbal and visual creativity. *Human Brain Mapping*, *38*(4), 2094–2111. https://doi.org/10.1002/hbm.23507