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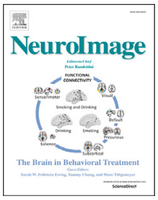

Creativity slumps and bumps: Examining the neurobehavioral basis of creativity development during middle childhood

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ABSTRACT

Developmental research has found that children's creative thinking ability tends to decline during middle childhood. However, this decline has not been consistently demonstrated, and the underlying neural and behavioral factors that affect fluctuations in children's creative thinking ability remain uncharacterized. Using a longitudinal cohort-sequential experimental design, we investigated the neurobehavioral basis of creative thinking ability during middle childhood in a sample of 48 children ($n = 21$ starting 3rd grade, $n = 27$ starting 4th grade) assessed longitudinally at three time-points across one year. For the first time, we used data-driven methods to reveal distinct trajectories in creative thinking ability during middle childhood. We found that although some children show a classic decline in creative ability, others exhibit a significant *increase* in creativity over time. These trajectories were not associated with differences in intelligence, age, or sex, but rather other developmentally-relevant constructs, including heightened externalizing behavior (i.e., rule-breaking and aggression). Using functional near-infrared spectroscopy (fNIRS) in a smaller cohort ($n = 26$), we examined longitudinal changes in bilateral frontal neural connectivity and found that increased right lateral frontal segregation or functional specialization tracked developmental improvements in creative thinking ability. Taken together, the findings reveal distinct profiles of change in creative thinking ability during middle childhood and identify behavioral and neural mechanisms potentially underlying changes in children's ability to think creatively.

1. Introduction

Creativity is commonly conceived as a cognitive ability responsible for generating original and appropriate ideas, insights, and solutions (Dietrich and Kanso, 2010). Creative thinking is becoming increasingly vital for career success in contemporary society (Hennessey and Amabile, 2010). With the advent of Artificial Intelligence, the demands of the labor force will continuously evolve towards more innovative thinking. Given the critical importance of creative thinking, several studies have been conducted to understand the neurocognitive mechanisms involved in creative thought processes (Dietrich and Kanso, 2010; Fink et al., 2007; Saggar et al., 2015), whether creative capacity can be enhanced by training (Fink et al., 2015; Onarheim and Friis-Olivarius, 2013; Saggar et al., 2017; Stevenson et al., 2014), and how creative ability changes over the course of development (Cousijn et al., 2014; Kleibeuker et al., 2016). Studying the development of creativity has been of keen interest in light of a widely-reported decline in creative thinking in middle childhood known as the “fourth grade slump”—a phenomenon linked to underachievement and increased risk for mental health problems (Torrance, 1968) that has been observed across cultures (Timmel, 2001) and continents (Raina, 1980).

Why does creative ability fluctuate during middle childhood? It has been proposed that, like other cognitive abilities and behaviors, creative ability follows a curvilinear trajectory consisting of peaks and slumps (Friend, 2004; Piaget, 1977). Others have argued that a slump in creative ability could be associated with the initial teaching of socialization and conformity behaviors (i.e., classroom etiquette and peer pressure) during child development (Camp, 1994; Smith and Carlsson, 1983; Torrance, 1968). Rosenblatt and Winner suggested that a conventional stage is manifested in child's behavior during development where he/she focuses on the representational accuracy of their work more than the aesthetic appeal (Rosenblatt and Winner, 1988), which may emphasize conformity of ideas and behavior over divergence and novelty. In addition to external causes, the intrinsic organization of the brain during

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development could also be responsible for the curvilinear trajectory of creative ability, especially the frontal cortex, which shows rapid maturation and reorganization during middle childhood (Fair et al., 2009; Grayson et al., 2014; Marek et al., 2015).

Although a decline in creativity during middle childhood has been widely reported across cultures, the timing of the slump has varied considerably from 3rd to 6th grade (Kim, 2011). Studies have also reported inconsistent findings, including a slight *increase* in creativity during fourth-grade (Claxton et al., 2005) or no change grade-wise (Sak and Maker, 2006). A close review of the literature suggests that such discrepancies could be due in part to variation within children (e.g., cognitive and personality traits) and across experimental designs. Individual differences could play an especially important role in studies where the data are grouped and examined solely based on academic grade (e.g., comparing 3rd versus 4th graders).

In the original work, Torrance (1968) found that only about half of the 4th graders demonstrated a slump in creative thinking compared to their own creativity scores in the 3rd grade (Torrance, 1968). The other half either did not show a slump or showed an increase in creativity scores. This finding suggests that grouping children based solely on their academic grade and computing group averages likely yields an inaccurate or incomplete picture. New data-driven approaches can better capture individual differences by clustering children based on creativity trajectories across development (cf., Fair et al., 2012 (Fair et al., 2012)). Another critical source of variation across studies is experimental design, with a majority of studies using cross-sectional methods (Kim, 2011). To better understand how and why creative capacity changes during middle childhood, a longitudinal approach examining various internal and external factors within a given child is essential.

In the present work, we designed a cohort-sequential study (see Fig. 1) to address the aforementioned methodological gaps and to advance our understanding of the neurobehavioral basis of creativity trajectories during middle childhood. Data were collected at three time points across one year. At each time point, behavioral and brain imaging data were collected using a battery of assessments (see Table 1). Creative ability was assessed using a standardized pen and paper task – the Torrance Test of Creative Thinking Figural (TTCT-F (Torrance, 1998)) – a widely used and well-validated standardized divergent thinking task requiring participants to complete incomplete figures (3 activities) that tell an unusual story. Functional Near-Infrared Spectroscopy (fNIRS) was used to collect bilateral prefrontal brain activation while participants were engaged in the TTCT-F and control tasks (see Fig. 2). We used fNIRS because it allows data collection in an ecologically valid setting (i.e., sitting upright and drawing using pen and paper) and is less prone to head movement artifacts relative to other neuroimaging modalities like fMRI (Perlman et al., 2013).

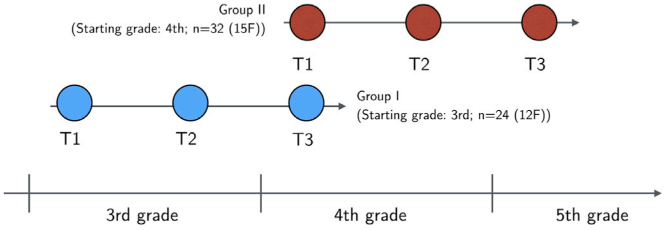

Fig. 1. A cohort-sequential semi-longitudinal study design to collect data across three grades (3rd – 5th) in one year. Two groups of children were enrolled in the study. The first group of children was starting their school session in 3rd grade, while the second group of children was starting their school session in 4th grade. Both groups were followed over a period of one year, and the data were collected at three time points (T1-T3) during the 1-year period. By design, for each group, we collected two data samples when the child was in his/her starting grade and one data sample when the child transitioned to the next grade.

Table 1
Participant's demographics at baseline or the first time point (T1) across the two groups of participants ($n = 48$). Group 1 started their 3rd grade and Group 2 started their 4th grade at T1. The child's intelligence was assessed using the WASI II (Wechsler, 1999). The standardized values for intelligence scores have a mean of 100 and S.D. of 10. The child's temperament was assessed using the EAS scale (Mathiesen and Tambs, 1999). The ability to inhibit responses and task switching was assessed using the NEPSY-II inhibition task (Brooks et al., 2009). Creative capacity was measured using the Torrance Test of Creative Thinking (Figural (Torrance, 1998)). To measure changes in child's aberrant behavior, we used the Children Behavioral Checklist (CBCL(Achenbach, 2015)). The normal range of CBCL Internalizing, Externalizing, and Total problem scale (t-score) are below 60.

	ASSESSMENT USED	GROUP 1	GROUP 2	*P-VALUE*
N	–	21	27	–
AGE [MEAN (SD)]	–	8.58 (0.31) yrs.	9.65 (0.41) yrs.	$p < 0.0001$
SEX [#F]	–	10 F	13 F	χ^2 ($p = 0.97$)
INTELLIGENCE [MEAN (SD)]	WASI II (FSIQ)	124.48 (11)	119.19 (10.27)	$p = 0.09$
CHILD'S ABERRANT BEHAVIOR [MEAN T-SCORE (SD)]	Total problem score Externalizing problem score Internalizing problem score	43.37 (11.12) 43.14 (10.23) 45.18 (9.56)	41.54 (11.23) 43.61 (9.35) 43.96 (10.74)	$p = 0.91$ $p = 0.87$ $p = 0.68$
RESPONSE INHIBITION [MEAN (SD)]	NEPSY-II inhibition Combined Scaled Score	11.81 (2.23)	9.80 (3.07)	$p = 0.02$
CHILD'S TEMPERAMENT [MEAN (SD)]	EAS Total Score	59.48 (5.77)	59.23 (4.44)	$p = 0.87$
CREATIVITY [MEAN (SD)]	TTCT-F Average Raw	11.83 (2.59)	13.49 (3.95)	$p = 0.10$

In contrast to using an arbitrary, academic-grade-based comparison between the two groups, we chose a graph-theoretical, data-driven approach to identify different profiles of curvilinear changes in creativity across groups. This approach was used to better address the individual differences previously observed in grade-based studies (Torrance, 1968). In addition to assessing longitudinal changes in creative ability, we assessed longitudinal changes in potential moderators known to be associated with development (e.g., response inhibition, parent-reported child's behavior, and temperament) including traits that have not been previously linked to creativity in childhood, but are theoretically relevant to creative thinking, such as "externalizing" behaviors (e.g., rule-breaking or aggression) that vary in their expression within *normative* child development. Altogether, for the first time, we examined longitudinal fluctuations in creativity during middle childhood using a cohort-sequential study design and assess corresponding changes in behavior, cognition, and brain function.

2. Materials and methods

2.1. Participants

Fifty-six healthy children participated in the study (mean age 9.20 years ± 7.5 months; 24 females, 32 males), who visited the lab at three different time points, i.e., fall of 2013, late spring of 2014, and fall of 2014. No major medical illness, neurological disorders, developmental delays, learning disabilities, or history of psychiatric illness were reported by the participants' parents. All participants were right-handed based on the Edinburgh Handedness Inventory. Participants were recruited through the local community using advertisements, and all participating children were enrolled in traditional elementary school programs in the Bay Area. The study protocol was approved by Stanford

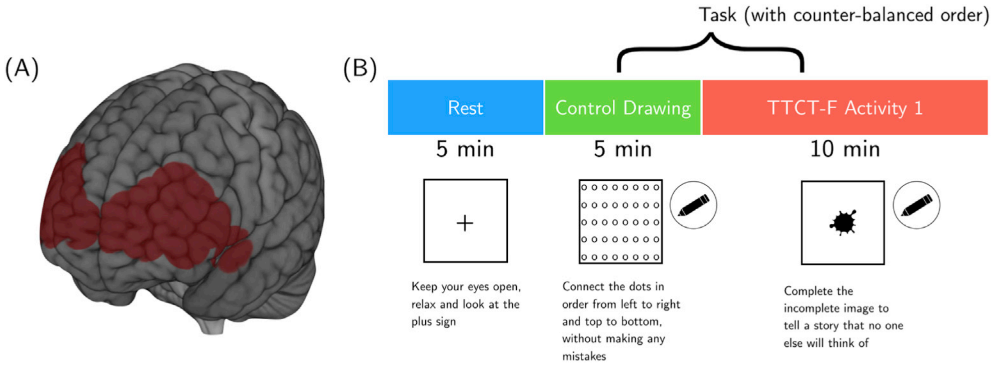

Fig. 2. Neuroimaging experimental design. (A) Shows bilateral prefrontal cortical regions (in red) that were assessed using functional Near-infrared Spectroscopy (fNIRS). (B) Shows the neuroimaging experimental design, which consisted of 5 min of resting state scan followed by 15 min of pen and paper tasks (including control drawing and creativity drawing (TTCT-F Activity 1)). The order of control drawing and creativity drawing was counterbalanced across participants and time points.

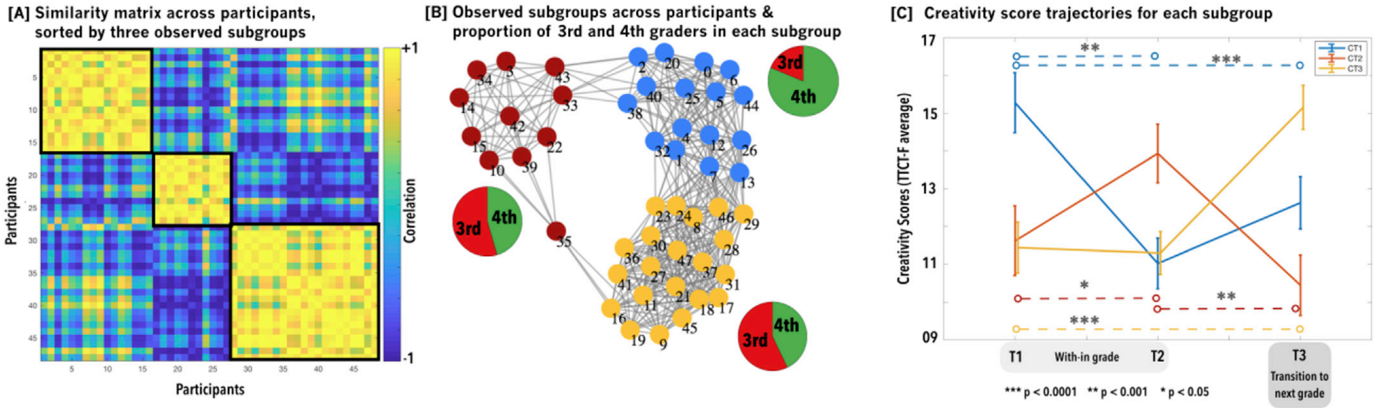

Fig. 3. Subgroups sharing similar creativity trajectories over time extracted using longitudinal TTCT-F Average Raw scores from $N_{behav} = 48$ participants. (A) Subgroups observed in the cohort. Based on how creativity scores change over time, three subgroups were found, as shown in the similarity matrix and the graph (B), which also shows the proportion of 3rd and 4th graders in each subgroup. (C) Shows creativity score trajectories for each subgroup, while controlling for the starting grade. The error-bar represents standard error of the mean. The creativity trajectory for subgroup 1 (CT1) shows a slump in creativity within their starting grade and a boom after transitioning to next grade, while the creativity trajectory for subgroup 2 (CT2) shows the inverse. For subgroup 3 (CT3), the creativity trajectory shows no change in creativity within starting grade and then a boom in creativity after transitioning to next grade. Asterisks (*) denote FDR-corrected p-values for the post-hoc t-tests (see Supplementary Table 6).

University's Institutional Review Board, and written informed consent was obtained from each child's parents. Out of the 56 children, complete behavioral data for all three time points were available for 48 children and useable neuroimaging data across all three time points were available for 26 children. More information about excluding criterion is provided in the following sections.

2.2. Behavioral assessments

NEPSY-II Inhibition task was used to assess cognitive inhibition. This task involves completing three activities – naming, inhibition, and switching, across two separate sets of stimuli (Brooks et al., 2009). To assess temperament the Emotionality, Activity, and Sociability (EAS-TS) scale was administered (Mathiesen and Tambs, 1999), while problem behavior was assessed using the Child Behavior Checklist (CBCL) (Achenbach, 2015). The creative capacity was assessed using the standardized Torrance Test of Creative Thinking-Figural (TTCT-F (Torrance, 1998)). To keep the assessments fun and game-like, both creativity and control drawing tasks were designed to be open-ended, single-block tasks of longer duration (5–10 min) as shown in Fig. 2. General intelligence was measured during the first visit using the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II). Complete behavioral data for all three points were available for forty-eight participants ($N_{behav} = 48$).

2.3. fNIRS data acquisition

The fNIRS data were collected using a 52-channel Hitachi ETG-4000 Optical topography system (Japan). Probes were placed using a standard 3 × 11 montage, resulting in 52 channels covering the prefrontal cortices on both hemispheres with inter-optode distance = 30 mm. The 3 × 11 montage was placed on each participant by visually inspecting the cranial landmarks of Nasion and Preaurical points (Supplementary Fig. 3). The absorption of near-infrared light at two wavelengths of 695 nm and 830 nm were measured with a sampling rate of 10 Hz. The concentration changes in oxy- and deoxy-hemoglobin for all channels was calculated using the modified Beer-Lambert law (Brigadoi et al., 2014).

The fNIRS scan consisted of a 20-min session, during which participants completed three separate tasks. All tasks took place while the participant was seated at a desk, and a chin-rest was utilized to ensure stillness. The order of the second (control drawing) and third tasks (creative drawing) was counterbalanced across participants and time-points. Participants were supervised by an experimenter during the session.

1. *Task 1: Resting state (300 s):* Participants were instructed to stay still, focus on the stimuli (fixation mark), and breathe normally for the duration of the task.

2. *Task 2: Control drawing (300 s):* Participants connected dots on paper in a prescribed pattern with instructions to "carefully connect dots from left to right and top to bottom, without making any mistakes."
3. *Task 3: Creative drawing (600 s):* Creative drawing included Activity 1 of TTCT-F. Scripted verbal instructions from the TTCT-F manual were provided, and each participant verbally confirmed their understanding of the procedure. During this task, participants were asked to incorporate a fixed shape into a novel drawing of their own and provide the drawing with a unique title.

2.4. Behavioral data analysis

To identify different curvilinear creativity development trajectories among participants ($N_{behav} = 48$), we first generated a similarity matrix (network) by correlating participant's TTCT-F average raw scores across the three time points, which were then fed to Louvain community detection algorithm (Blondel et al., 2008), resulting in subgroups/communities sharing similar longitudinal creativity trajectories. For robustness, community detection was run 1,000 times with additional consensus clustering run 100 times on the agreement matrix. To test against chance-level communities, we generated null models while preserving the degree-, weight-, and strength-distributions in networks with positive and negative weights of the original network. The above analysis was performed using the Brain Connectivity Toolbox for community estimation and consensus clustering (Rubinov and Sporns, 2010).

2.5. fNIRS data analysis

The neuroimaging data were first preprocessed using Homer 2 package in MATLAB (https://www.nitrc.org/projects/homer2) described by Brigadoi et al. (2014). Specifically, optical density data were corrected for motion artifacts using wavelet motion correction procedure. Bad channels (e.g., due to lack of contact with the scalp and technical difficulties) were removed from further analysis. Due to the relatively smaller head size of our participant pool, a significant number of channels from the top-row of the 3 × 11 patch and over the ear region did not touch the scalp in the majority of participants and time points (Supplementary Fig. 3). Thus, resulting in a total of 20 channels (instead of 52) with good contact with the scalp and were used for further analysis.

The anatomical locations for all NIRS channels were not acquired for the current cohort of participants. However, for visualization purposes only, anatomical locations of NIRS channels in relation to standard head landmarks were determined for a separate individual using a Patriot 3D Digitizer (Polhemus, Colchester, VT). The MNI coordinates for NIRS channels were then obtained using the MRIcroGL software (http://www.mccauslandcenter.sc.edu/mricrogl/home/). Fig. 2A shows approximate mapping on the cortical surface and Supplementary Table 3, provides approximate MNI locations for the fNIRS channels.

A band-pass filter with a cutoff frequency of 0.01 Hz and 0.5 Hz was applied before converting the optical density data to oxygenated and deoxygenated hemoglobin using the modified Beers-Lambert law. The oxygenated hemoglobin was used as a proxy of brain activity as it previously showed maximum agreement with functional fMRI BOLD signal. A smaller cohort of participants ($N_{fNIRS} = 26$) had useable fNIRS data across all three time points and was used for further analysis. The exclusion criterion for participants based on the availability of fNIRS data at all three time points as well as coverage of at least bilateral prefrontal regions.

After pre-processing, functional connectivity (FC) was estimated by averaging magnitude-squared wavelet coherence between all pairs of channels over 5 min of rest, the first 5 min of creativity and over 5 min of control assessments. The before-mentioned community detection procedure (section 2.4) was also used to partition fNIRS channels into communities using condition-specific FC. To estimate longitudinal changes in the network structure of the bilateral prefrontal brain regions, we used between-community interaction scores (B_T) as a measure of brain integration/segregation level (i.e., communication mainly occurs within or between communities) as shown in Equation (1):

$$B_{Ti} = 1 - \sum_{s=1}^{N} \left(\frac{\kappa_{is}}{\kappa_i}\right)^2 \tag{1}$$

Where B_T is the between-community interaction score of channel i; κ_{is} is the strength of the FC connections of channel i belonging to the community s; κ_i is the total strength of all connections of channel i; N is the total number of communities detected by Louvain algorithm. Hence, B_T is between zero (all communication is within its own community) and one (all communication is uniformly distributed across all the communities).

3. Results

3.1. Participant demographics

Table 1 provides overall demographic information for participants at baseline (or T1). As expected, participants in Group 1 (3rd graders) were significantly younger than Group 2 (4th graders). However, the two groups were balanced in terms of sex ratio and IQ scores. Supplementary Tables 1 and 2 provide additional information about the participant and parent demographics.

3.2. Data-driven trajectories of creativity

To better account for individual differences, we used a data-driven examination of raw TTCT-F scores gathered across three time points (T1-T3) in the combined pool of all participants. Out of the initial pool of 56 participants, TTCT-F scores at all three points were available for 48 participants.

Our overarching aim was to identify different curvilinear creativity development trajectories among all participants. Three creativity trajectories were revealed across all participants as shown in Fig. 3. The creativity trajectories retrieved from the data were significantly more robust as compared to the chance level (Z = 69.9; Supplementary Fig. 1). The trajectory of creativity scores across the three time points is shown in Fig. 3B. A repeated measures ANOVA was utilized controlling for the starting grade (see Section 2.2); trajectories were the between-subjects factor and time was the within-subject factor. A significant Trajectory × Time interaction was observed (F (4,88) = 34.78, $p = 2.14 \times 10^{-17}$), suggesting a difference between the three trajectories in terms of how creativity scores change over time.

Post-hoc analysis revealed that among the three creativity trajectories, the first creativity trajectory (CT1) showed a slump in creativity within their starting grade (i.e., T1 to T2; FDR-corrected $p < 0.00001$) and a boom after transitioning to next grade (i.e., T2 to T3; FDR-corrected $p = 0.042$), while the second creativity trajectory (CT2) showed the inverse pattern, i.e., a boom in creativity within their starting grade (FDR-corrected $p = 0.0061$) and a slump after transitioning to next grade (FDR-corrected $p = 0.0001$). The third creativity trajectory (CT3), showed no change within their starting grade ($p = 0.96$) and a boom in creativity after transitioning to next grade (FDR-corrected $p < 0.00001$). Supplementary Tables 5–6 provide a tabular summary for ANOVA and post-hoc results.

3.3. Assessing the effect of intelligence, sex, and grade on the creativity trajectories

To examine whether the three creativity trajectories were observed primarily due to differences in factors of IQ, age, sex, or starting grade, a one-way ANOVA and Chi-Square test of independence was performed. There were no significant group differences of creativity trajectories on

IQ (F (2,45) = 2.04, $p = 0.14$), or age (F (2,45) = 0.58, $p = 0.56$) using one-way ANOVA (see Supplementary Table 4 for a statistical summary). Chi-Square test of independence suggested that there was no difference in gender χ (2, N = 48) = 4.159, $p = 0.125$, while a significant difference across creativity trajectories in starting grade χ (2, N = 48) = 6.115, $p = 0.047$, suggesting that the grade distribution was different across creativity trajectories (shown as pie-charts in Fig. 3A; Supplementary Table 4 for statistical summary). Due to the observed difference in grade distribution across the three profiles, the starting grade was used as a covariate for all analyses reported in this work.

3.4. Response inhibition and creativity trajectories

To examine the relationship between response inhibition and creativity, we first examined whether these two constructs were correlated at baseline (T1), while controlling for starting grade and using data pooled across all participants. No significant association was observed between the NEPSY II sub-scores of naming, inhibition and switching, and average raw TTCT-F creativity scores.

Next, to examine whether developmental changes in response inhibition over time could explain the observed creativity trajectories, we ran repeated measures ANOVAs using NEPSY II inhibition scores, with creativity trajectory as a between-subjects factor and time as a within-subject factor. None of the sub-components of NEPSY (i.e., naming, inhibition, or switching scores) revealed a significant creativity trajectory × time interaction, suggesting that the observed differences in creativity trajectories were not associated with longitudinal changes in response inhibition.

3.5. Child's temperament and creativity trajectories

The child's general temperament was assessed by administering the Emotionality, Activity, and Sociability (EAS-TS) scale to parents. Similar to response inhibition analysis, we first examined whether temperament and creativity were correlated at baseline (T1) while controlling for starting grade. Among the sub-scales (Emotion, Shyness, Activity, and Social), Shyness was observed to be negatively associated with average TTCT-F creativity scores (*rho* = −0.41, $p = 0.0036$; Fig. 4A). This association suggests that participants with shy temperament had lower creativity scores. No significant creativity trajectory × time interaction was observed for any of the four sub-components of the child's temperament scale.

3.6. Children's problem behavior and creativity trajectories

The Child Behavior Checklist (CBCL) was used by parents to report any identifying problem behavior in children at each time point. The CBCL consists of two broad-band scales for identifying Internalizing and Externalizing problems; it also contains a third scale to report total problems. The Internalizing scale includes the Anxious-depressed, Withdrawn-depressed, and Somatic-complaints scores, while the Externalizing scale combines Rule-breaking and Aggressive behaviors.

Similar to response inhibition and temperament analysis, we first examined associations of creativity score with the two broad scales as well as the total problems scale of CBCL. For externalizing problems, controlling for starting grade, we observed a significant positive association with the TTCT-F average scores (Spearman's *rho* = 0.30, $p = 0.034$; Fig. 4B). This finding suggests that higher externalizing behavior is positively associated with creativity.

For longitudinal analysis, a significant creativity trajectory × time interaction was observed for the total problems scale (F (4,72) = 2.86, $p = 0.03$), such that the total problem scores for creativity trajectory CT1 (i.e., slump → boom) were lower at T3 compared to T1 (post-hoc *t*-test *p (uncorrected)* = 0.009 and FDR-corrected p = 0.08; Fig. 4C). We also observed a statistically non-significant creativity trajectory × time interaction for the externalizing problem scores (F (4,72) = 2.08, $p = 0.09$), with a similar direction of decline in scores for the creativity trajectory CT1 and an increase for creativity trajectory CT3 (i.e., no change → boom).

3.7. Identifying the neural correlates of creativity trajectories

Before performing longitudinal analyses with fNIRS data, we first assessed whether the creativity trajectories, derived from the original cohort of participants ($N_{behav} = 48$), were preserved in the smaller cohort of participants ($N_{fNIRS} = 26$) with useable fNIRS data across all time points (T1-T3). Critically, even for this smaller cohort, the Repeated Measures ANOVA (controlling for starting grade) revealed a significant creativity trajectory × time interaction for TTCT-F average scores (F (4,44) = 23.76, $p = 1.63 \times 10^{-10}$), with similar trajectories for each profile as seen in the larger cohort (Fig. 5A).

To assess the neural correlates of the observed creativity trajectories, we estimated longitudinal changes in the brain network integration/segregation levels from the bilateral prefrontal regions. For this assessment, we used fNIRS data acquired while participants were resting with eyes-open and engaged in the pen-and-paper creativity and control

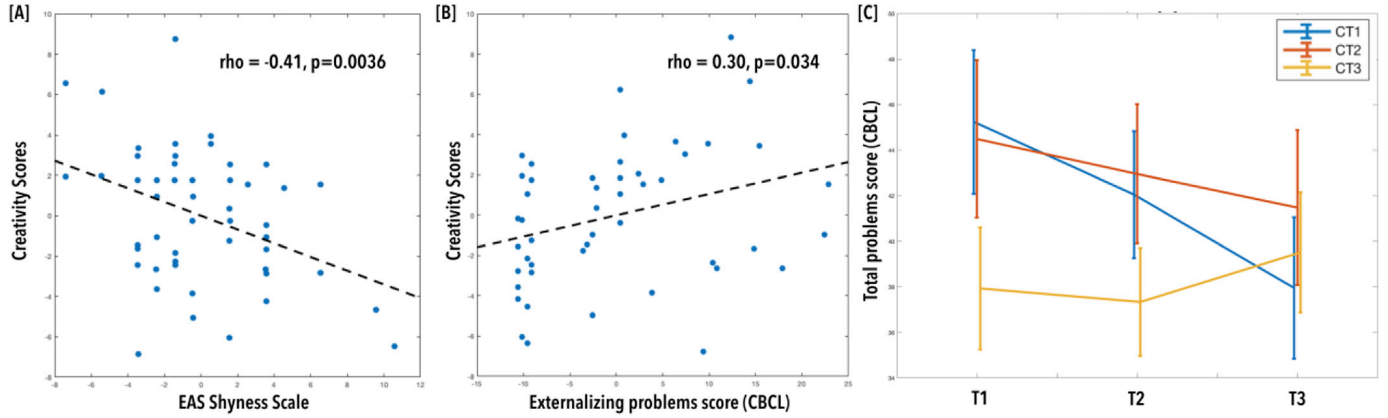

Fig. 4. Child's temperament, aberrant behavior, and creativity. (A) Depicts observed negative correlation between Creativity scores and EAS Shyness scale at baseline, while controlling for starting grade. (B) Depicts observed positive correlation between Creativity scores and CBCL Externalizing scale that includes rule-breaking and aggressive behavior at baseline) while controlling for starting grade. See Supplementary Fig. 2 for a distribution of Externalizing behaviors in our cohort. (C) Depicts variations in the mean of Total problems scale from CBCL for each creativity trajectory.

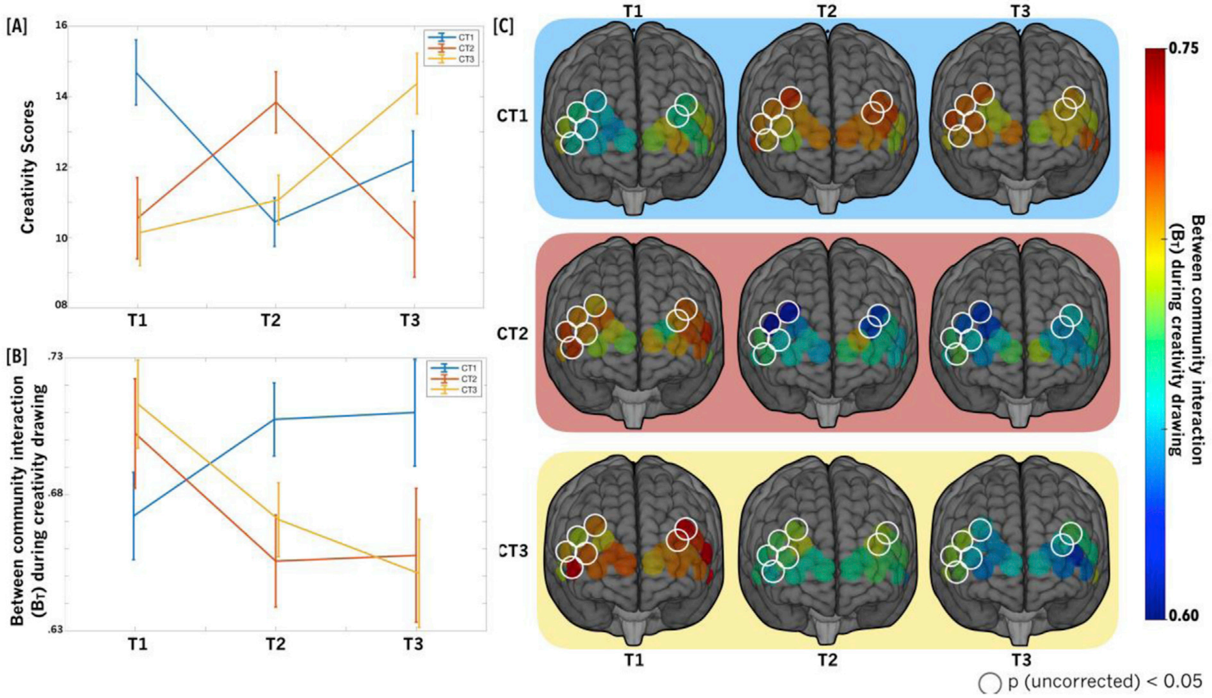

Fig. 5. Identifying neural correlates of creativity trajectories. (A) Shows preserved trajectory of creativity scores for each of the three profiles in a smaller cohort of $N_{fNIRS} = 26$ with fNIRS data at all three time points (as compared to the larger cohort of $N_{behav} = 48$). (B) Significant creativity trajectory × time interactions were observed for the mean (across all regions) B_T scores during creativity drawing assessments. (C) Shows post-hoc analysis to reveal the brain regions driving the creativity trajectory × time interaction observed during creativity and control assessment conditions, respectively. Blue circles denote individual channels driving significant interactions ($p < 0.05$).

drawings (Fig. 2A). For creativity assessment, participants were instructed to complete the Activity-1 from their TTCT-F booklet (duration: 10 min). For the control drawing, participants were instructed to carefully connect the dots on a sheet (duration: 5 min; see Methods). After pre-processing, fNIRS data were used to estimate mean functional connectivity between brain regions using a magnitude-squared wavelet coherence method (Bassett et al., 2011). The mean functional connectivity was estimated separately over the first 5 min of rest, creativity task, and control assessments. To assess the longitudinal changes in the integration/segregation levels, we estimated the communities of channels with similar activity profiles and then computed between-community interaction (B_T) scores (see Section 2.5). The B_T score is a measure of brain network integration/segregation for each channel, e.g., higher B_T indicates more integrated brain network structure. Finally, we conducted three repeated measures ANOVAs (one for each condition – rest, control drawing, and creative drawing) on B_T scores with creativity trajectory as a between-subjects factor and time as a within-subject factor.

Results revealed a significant creativity trajectory × time interaction for B_T scores during creativity (F (4,44) = 3.59, $p = 0.013$) and control drawing (F (4,44) = 5.45, $p = 0.0012$). No significant trajectory × time interaction was observed for B_T scores during resting state (F (4,44) = 0.85, $p = 0.50$). Comparing Fig. 5A and B, we observed that there might exist an inverse relationship between mean B_T scores and creativity scores over the three time points for all three creativity trajectories (CT1-3), suggesting increased frontal segregation or functional specialization might be associated with creativity. Post-hoc region-level analysis revealed that the creativity trajectory × time interaction of B_T scores was driven mostly by the right prefrontal regions for creativity drawing (Fig. 5C).

During the control drawing condition, the significant creativity trajectory × time interaction of B_T scores is shown in Supplementary Fig. 4A. The interaction was driven mostly by creativity trajectory CT2, such that reduced B_T scores were observed at T2 and T3 as compared to T1. Further, post-hoc analysis at the level of individual channels revealed that the trajectory by time interaction of B_T scores was driven by nearly all regions (Supplementary Fig. 4B).

3.8. *Relating changes in creativity with observed frontal segregation*

We performed a linear mixed effect (LME (Bates et al., 2015)) analysis to more rigorously test the relationship between the average frontal integration level (B_T) during creativity task and TTCT-F raw scores, as both of them separately showed a significant creativity trajectory × time interaction. After standardizing B_T and TTCT-F scores, a full LME model was fitted with the fixed effects being B_T, starting grade, time point and a random intercept for participants to predict TTCT-F scores. We created a reduced model without the main effect of interest (i.e., mean B_T) and performed a likelihood ratio test of the two models to obtain the p-value. We found a significant negative relationship between B_T and TTCT-F scores ($t = -2.20$, $p = 0.03$), confirming our observation that functional specialization in frontal regions is associated with the creative ability (see Supplementary Table 8 for a statistical summary). A small to medium effect size was found to be 0.119 using Cohen's f.

4. Discussion

Using a cohort-sequential experimental design and a data-driven methodology, we uncover distinct developmental trajectories in creative ability across middle childhood. These trajectories were related to specific behavioral factors, including externalizing behavior (within *normative* developmental ranges) that was positively associated with creativity. Moreover, we found that developmental change in creativity tracked brain development in the right frontal lobe: as creativity increased over time, the right lateral prefrontal cortex showed increasing segregation or functional specialization. In sum, our findings reveal the existence of three developmental trajectories in creative thinking ability—highlighting the importance of heterogeneity when studying the development of creativity during middle childhood—and identify distinct neural and behavioral factors that track changes in children's creative ability over time.

The three developmental trajectories were characterized by distinct patterns of change in creative ability during middle childhood. Briefly, CT1 showed a slump in creativity within their starting grade and a boom after transitioning to the next grade. CT2, on the other hand, showed the inverse pattern: a boom in creativity within their starting grade and a slump in their next grade. Interestingly, CT3 showed no change during their starting grade and a boom in creativity in their next grade. This data-driven approach thus reveals that children vary in the onset of the creativity slump, with some children showing earlier declines (CT1), some showing later declines (CT2), and others showing no decline and a substantial increase (CT3). These findings help to clarify past work reporting mixed evidence for the existence and timing of declines in creative ability by identifying groups of children that vary in terms of how and when their creative abilities change over time. Importantly, these trajectories were observed even in the smaller subset of the cohort available for brain imaging, suggesting that the trajectories are relatively robust to sample size.

What factors drive change in creative ability across development? We attempted to address this question by longitudinally assessing a range of behavioral and neurophysiological markers. We found that children's problem behavior was positively associated with creativity, both at baseline and across the three time points. Although children in our study had CBCL scores in the normal range (as defined in Achenbach and Rescorla, 2001), our data suggest a significant positive relation between externalizing problem behavior (i.e., rule-breaking and aggressive behavior) and creativity. Rule-breaking behavior has previously been linked to creativity (Gino and Wiltermuth, 2014) and it may be consistent with the lay notion of "thinking outside the box" to create unusual and novel ideas (Hennessey and Amabile, 2010). Classic creative thinking tasks, such as tests of divergent thinking, require people to break rules between cognitive elements (e.g., associations) to form new links between previously unassociated elements (Guilford, 1950). Interestingly, in our study, other behavioral markers of child's temperament and cognitive markers of response inhibition did not correspond with the longitudinal changes in creativity. Thus, the common cognitive and neural mechanisms of rule-breaking and creativity remain unclear—as does the causal influence of the two variables—so future research is needed to clarify this question.

The linear mixed effects analysis revealed that an increase in segregation (or functional specialization) of frontal brain networks is associated with an increase in creative thinking ability. A balance between regional specialization and global integration of individual brain regions is essential for maintaining the meta-stability of complex dynamical systems of the brain (Tononi et al., 1994). Previous studies examining brain network topology while participants were engaged in cognitive tasks have reported an increase in global integration between brain regions during cognitive tasks that require effortful processing and deliberate cognitive control (e.g., n-back working memory task (Shine and Poldrack, 2017) and directed or sustained attention during other executive functioning tasks (Cohen and D'Esposito, 2016). Similarly, segregation or functional specialization of brain regions has been previously associated with tasks requiring diffuse attention or automaticity (Bassett et al., 2015). In other words, the brain seems to benefit by switching between local segregation of information processing during sensory encoding (Sadaghiani et al., 2015) and task learning (Bassett et al., 2015), and global integration processing during working memory (Shine and Poldrack, 2017) and cognitive control tasks (Cohen and D'Esposito, 2016). Post-hoc analysis showed that right prefrontal regions drove the significant creativity trajectory × time interaction for mean segregation scores. This result is in line with previous work suggesting a pivotal role of prefrontal cortex in supporting creative behavior (Dietrich and Kanso, 2010; Gonen-Yaacovi et al., 2013; Kowatari et al., 2009). Our findings advance previous studies by demonstrating the importance of functional specialization of the prefrontal cortex (especially right prefrontal cortex) for creative thinking ability during middle childhood.

5. Limitations and future directions

The present study is the first to use data-driven methods to identify distinct developmental trajectories and neurobehavioral correlates of creative thinking during middle childhood. Despite the strengths of the current work, several limitations are worth noting. First, instead of tracking the same cohort of children for 2 years, we used a cohort-sequential (or accelerated longitudinal) design to expedite data collection. However, the data-driven method used to identify creativity profiles over time may have mitigated the limitations of the cohort-sequential design, especially compared to alternative approaches using academic-grade-based cut-offs to compare groups. Second, only a subset of students ($N_{fNIRS} = 26$) from our total cohort ($N_{behav} = 48$) was available for neuroimaging. Due to technical difficulties, we could not collect neuroimaging data in all participants at all time points, thus we limited the fNIRS analysis to participants who had useable data at all three time points. Critically, the creativity profiles identified in the full cohort were still evident in the smaller cohort with useable fNIRS data. Third, our study focused on a subset of potential moderators of creativity development (i.e., response inhibition, parent-reported child's behavior, and temperament). Although these moderators were motivated by their empirical and theoretical relevance to creativity, we suspect that other factors may also influence creative trajectories in childhood (e.g., openness to experience and creative self-efficacy). Fourth, our study examined creativity change within a relatively brief period of development (i.e., 3rd and 4th grade) due to our interest in examining the neurobehavioral basis of the "fourth-grade slump." We encourage future investigations on the neurodevelopment of creativity to examine other potentially relevant moderators across a wider range of middle childhood.

The fifth factor concerns the inherent limitations of the neuroimaging modality (i.e., fNIRS) which is a region-of-interest-based modality that does not provide whole-head coverage. Further, fNIRS is only capable of measuring hemodynamic changes in the cortical surface. Thus, our neuroimaging analysis and the associated results are limited to bilateral prefrontal regions of the brain. Due to the young age group of our participants, we chose fNIRS instead of other standard modalities like fMRI and EEG. As compared to lying motionless for long periods in an MR-scanner, fNIRS provides an ecologically valid study design, i.e., sitting upright and drawing with pen and paper on a desk (Xue et al., 2018). Further, as compared to EEG, fNIRS provides better spatial resolution and less susceptibility to head movement (Perlman et al., 2013). Lastly, another potential caveat is the lack of prior power analysis to determine the optimal number of participants, which may have caused this study to be underpowered.

6. Summary and conclusions

The main aim of the present study was to better understand how and why creative ability changes in middle childhood. Using data-driven methods, we discover three developmental trajectories in creative thinking ability—extending past work using grade-based cutoffs—thus revealing that children vary in the onset and direction of change in this important cognitive ability. We identify neural and behavioral predictors of changes in creative thinking over time, including novel neurobehavioral evidence for the association between externalizing behavior (i.e., rule-breaking and aggressive behavior) and functional specialization of frontal brain networks. While the current work sheds new light on the neurodevelopment of creativity, we encourage future work to further characterize how and why children vary in their ability to think creatively.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.03.080.

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