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Creative thinking and brain network development in schoolchildren

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Abstract

Fostering creative minds has always been a premise to ensure adaptation to new challenges of human civilization. While some alternative educational settings (i.e., Montessori) were shown to nurture creative skills, it is unknown how they impact underlying brain mechanisms across the school years. This study assessed creative thinking and resting-state functional connectivity via fMRI in 75 children (4–18 y.o.) enrolled either in Montessori or traditional schools. We found that pedagogy significantly influenced creative performance and underlying brain networks. Replicating past work, Montessori-schooled children showed higher scores on creative thinking tests. Using static functional connectivity analysis, we found that Montessori-schooled children showed decreased within-network functional connectivity of the salience network. Moreover, using dynamic functional connectivity, we found that traditionally-schooled children spent more time in a brain state characterized by high intra-default mode network connectivity. These findings suggest that pedagogy may influence brain networks relevant to creative thinking—particularly the default and salience networks. Further research is needed, like a longitudinal study, to verify these results given the implications for educational practitioners. A video abstract of this article can be viewed at https://www.youtube.com/watch?v=xWV_5o8wB5g .

KEYWORDS
brain networks, creativity, functional connectivity, Montessori, pedagogy

Research Highlights

- Most executive jobs are prospected to be obsolete within several decades, so creative skills are seen as essential for the near future.
- School experience has been shown to play a role in creativity development, however, the underlying brain mechanisms remained under-investigated yet.
- Seventy-five 4–18 years-old children, from Montessori or traditional schools, performed a creativity task at the behavioral level, and a 6-min resting-state MR scan.

- We uniquely report preliminary evidence for the impact of pedagogy on functional brain networks.

1 | INTRODUCTION

We live in a constantly changing environment, increasing in complexity. To face the new challenges that arise, adaptability is key. One way to adapt is through creative thinking, the process of generating new and useful ideas (Sternberg & Lubart, 1996). While creative thinking increases across childhood (Eon Duval et al., 2022), schooling experience was shown to nurture its development (Besançon & Lubart, 2007; Denervaud et al., 2019; Lillard & Else-Quest, 2006). Lately, there has been an increasing interest in understanding the underlying functional brain network processes of creative thinking. Increasing neuroscientific evidence suggests that creative thinking involves functional connectivity between specific large-scale brain networks (Beaty et al., 2016; Beaty, Kenett et al., 2018; Beaty et al., 2019; Li et al., 2017). However, almost all these studies have been conducted with adults, leaving unexplored how these brain networks develop in children and the extent to which school pedagogy impacts them.

Creative thinking is beneficial at the individual level through its contribution to mental flexibility and management of unexpected events, and at the collective level through its role in innovation (Runco, 2004). Recent work in network neuroscience has revealed three main functional brain networks involved in creative thinking processes: the Default Mode Network (DMN), the Executive Control Network (ECN), and the Salience Network (SN) (Beaty et al., 2016; Beaty, Chen et al., 2018; Beaty, Kenett et al., 2018).

The DMN is associated with cognitive tasks involving spontaneous as well as self-generated thought like mind wandering, mental simulation, or social cognition (Smallwood et al., 2021). It is also implicated in creative thinking for idea generation (Beaty et al., 2014, 2020). The ECN is associated with tasks involving cognitive control like working memory, relational integration, as well as task-set switching (Dixon et al., 2018) and is implicated in creative thinking for idea evaluation or elaboration (Cai et al., 2016). Prior work has shown that highly creative individuals—people who show high scores on creative thinking tests—show increased functional connectivity between the DMN and ECN (Beaty, Kenett et al., 2018).

DMN-ECN co-activation during creative thinking is thought to be facilitated by a flexible switching mechanism within the SN. Indeed, the SN's primary function is to focus on one stimulus when multiple stimuli are competing for our attention (Uddin et al., 2010). In the context of creative thinking, it is important for switching between the DMN and the ECN in other tasks (Menon & Uddin, 2010). The SN is theorized to identify candidates amongst ideas within the DMN and select the most appropriate ones. Then, those ideas are forwarded by the SN to the ECN, where they are evaluated and elaborated (Beaty, Kenett et al., 2018). The ECN may also act on the mechanism of idea generation to evaluate and adjust useful ideas, and sometimes suppress unoriginal ideas (Beaty et al., 2017). This feedforward loop allows adjusting ideas to specific goals (Beaty et al., 2016). Taken together, these findings indicate how the interplay between the DMN, ECN, and SN is central to creative thinking abilities. Despite advances in the understanding of the underlying neural processes of creative thinking, few studies have investigated their development, as well as their sensitivity to school experience.

Across development, functional connectivity undergoes drastic reorganization (Uddin et al., 2010). Brain network maturation leads to the reduction of local functional connectivity in favor of increased distal functional connectivity (Kelly et al., 2009). More specifically, a study comparing the DMN, ECN, and SN of children (7–9 years old) with young adults (19–22 years old) reported stronger functional connectivity between these brain networks and increased SN influence across development (Uddin et al., 2011). Furthermore, intra-network functional connectivity increases within the DMN and ECN up to adulthood (Fair et al., 2008; Sherman et al., 2014). While these developmental changes occur, experience may modulate how these networks relevant to creative thinking will spatially and dynamically function. Recent studies linking behavioral outcomes and functional connectivity revealed processes of experience-dependent plasticity: brain regions showed changes in co-activation patterns following training in reasoning, working memory, multitasking, or mind and body integration (Mackey et al., 2013; Takeuchi et al., 2013, 2014; Xue et al., 2011). Experience-dependent plasticity at the neural level would corroborate developmental findings in creative thinking outcomes and point to the potential importance of schooling experience in shaping brain networks relevant to creative thinking.

Throughout childhood, creative thinking follows a non-linear developmental pattern. An early, steady increase is followed by bumps and slumps during the school years (Barbot et al., 2018). While creative thinking is highly associated with executive functions (Benedek et al., 2018) that undergo substantial changes across childhood (Davidson, 2006), school experience also influences creative thinking in children. Children experiencing a more normative environment (i.e., traditional pedagogy)—with mainly teacher-directed curricula, grades, and same-age competitive settings (Hayek et al., 2017)—showed lower performance on creative thinking tests (Fleming et al., 2019). Conversely, children experiencing alternative pedagogy, like Montessori schools—where children work within multi-age cooperative classes with self-exploratory activities and no grades—exhibited higher creative thinking skills (Besançon & Lubart, 2007; Denervaud et al., 2019; Lillard & Else-Quest, 2006). These studies provide evidence that experience at school can impact creative thinking abilities (Denervaud et al., 2021; Eon Duval et al., 2022), raising questions about underlying brain processes. However, no research exists linking the maturation of functional brain networks, the development of creative thinking, and school pedagogy.

To address this gap, we leveraged resting-state functional magnetic resonance imaging (fMRI) data and standardized creative thinking measures in 75 schoolchildren experiencing either the Montessori ($N = 37$) or the traditional ($N = 38$) pedagogy from an early age. Our goal was to explore the interactions between age, creative thinking, and the underlying functional brain networks at the static and dynamic connectivity levels. A static connectivity analysis allows a global investigation of between- and within-network activity (Patil et al., 2021). However, because static connectivity averages the brain signal, obscuring the dynamic interactions between networks over time, we also conducted a dynamic functional connectivity analysis.

We hypothesized an effect of pedagogy on functional connectivity at the static and dynamic levels. More specifically, we expected: (1) higher creative thinking abilities in Montessori-schooled children than in their peers from traditional schools, replicating previous work in the field (e.g., Besançon & Lubart, 2007; Denervaud et al., 2019; Eon Duval et al., 2022; Lillard & Else-Quest, 2006) and this effect to be reflected; (2) in the SN showing hyperactivity in traditionally-schooled children, impairing its switching activity with other networks such as the DMN and the ECN, as suggested in previous work on error monitoring (Denervaud et al., 2020); and (3) this hyperactivity to impede flexible switching from the DMN to ECN, reflected by higher intra-DMN and/or intra-ECN connectivity.

To our knowledge, this is the first study to examine how school pedagogy impacts the development of brain networks that support creative thinking. Understanding how pedagogy impacts creative thinking processes in schoolchildren at the neural level has potential implications for educational practices that aim to foster creative thinking.

2 | MATERIALS AND METHODS

2.1 | Participants

Children were recruited in partner schools in Switzerland and invited to the Radiology Department at the University Hospital of Lausanne. In total, 99 children were enrolled in this study between 2018 and 2021. Inclusion criteria were age (4–18 years old), enrolled in either Montessori or traditional schools since the beginning of their school curriculum, and with no history of neurological disorder. A written consent form was filled in by a legal guardian of the participant. The local ethics committee approved this study (CER-VD). A total of 24 children were excluded due to excessive head movement ($n = 8$), lack of creative thinking measures (n = 11), or interference with magnetic resonance imagining (MRI) scanner due to a dental brace ($n = 5$), leaving a final sample of 75 children (4.6–18.0 y.o.; 9.84 y.o. ± 2.63 y.; 43 females) for the current study. Out of the 75 children, 37 children (4.6-18.0 y.o.; 9,69 y.o. ± 2.79 y.; 19 females) attended a Montessori school, and 38 children (5.2–15.2 y.o.; 9.98 y.o. ± 2.49 y.; 24 females) attended a traditional school.

2.2 | Demographics and group variables

In Switzerland, Montessori schools are private systems only. To control for a possible selection bias, group variables were collected to check that participants from the two pedagogy groups (Montessori, traditional) were comparable in terms of fluid intelligence, socio-economic background, parental interest in pedagogy, and educational style at home (see operationalizations below).

Fluid intelligence was assessed using a paper-based, black-and-white version of the Raven's Progressive Matrices (PM-47) test (John & Raven, 2003), composed of 36 matrices divided into three sets of 12 matrices. Each of the matrices had a missing part. The child was asked to select one of the six or eight pieces that would complete the matrix (task duration = 15 min). Summing correct answers yielded a total score, which ranged from 0 to 36.

Socio-economic status, interest in pedagogy, and parental style were collected from the parents through online or paper-based questionnaires:

- Socio-economic status (SES): parents were instructed to complete a form about their educational and professional levels (Genoud, 2011). The answers given by each parent were summed and then averaged in the case where the child is under bi-parental authority. In the case of mono-parental authority, the sum was the final score. The maximum was four.
- Interest in pedagogy: parents answered three questions about their interest in pedagogy and education (e.g., "do you read books about child development?"). The sum of each answer was used. The maximum score was three.
- Parental style: parents answered four questions about the home environment (e.g., type of family activities, access to green space). Each question was scored and normalized independently, and the final score was derived by summing all answers. A higher score reflected an enriched home environment. The maximum score was four.

Multiple t-tests were performed for each variable between the two groups (Montessori, traditional) using Jamovi (https://www.jamovi.org). Finally, a Chi-square test was computed to verify whether the gender ratio was comparable between the two groups.

2.3 | Creative thinking assessment

Literature combined with recent work from our lab shows that convergent thinking measures show fewer "bumps" and "slumps" across age (compared to divergent thinking), with a more linear development (e.g., Eon Duval et al., 2022), we decided this measure to be a better marker of creativity. Furthermore, convergent thinking in very young children (<6 yo.) is easier to grasp in our experience, compared to divergent thinking. Convergent thinking involves producing a single solution to a creative problem (e.g., integrating objects to make a drawing), as opposed to divergent thinking, which involves producing multiple pos-

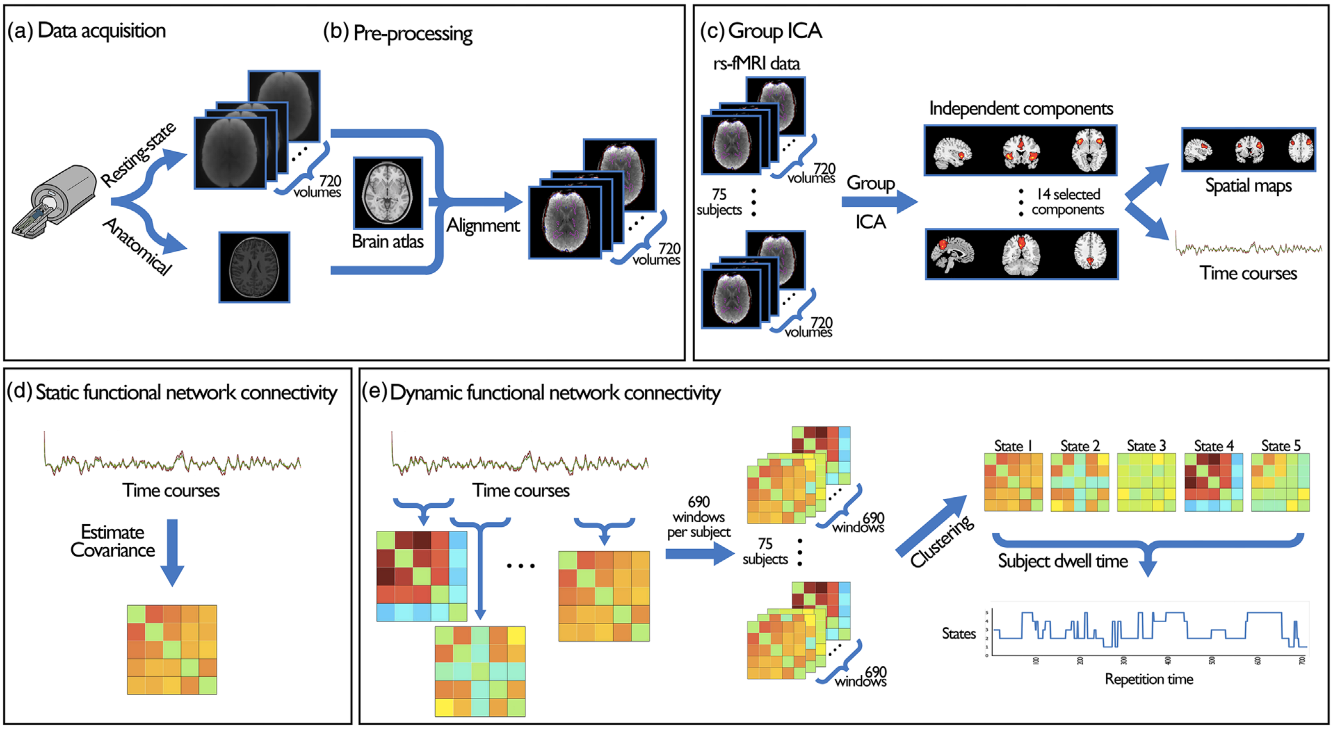

FIGURE 1 Schematic representation of the analysis pipeline. (a) Anatomical and resting-state data acquisition. (b) Imaging data preprocessing using fMRIPrep 20.2.1. (c) Group ICA of resting-state functional magnetic resonance imaging (rs-fMRI) data using GIFT toolbox and selection of the ICs for the three networks of interest (DMN, SN, ECN). This allowed for spatial maps and time courses to be generated from voxel activity. (d) Static functional network connectivity (sFNC) was performed on the average time courses of all children, for each IC, to generate spatial maps, time courses spectra, and FNC correlations. (e) Dynamic functional network connectivity (dFNC) was performed on the entire time course of each child. A window-based approach was used to divide the signal into small windows of the same length which was followed by a *k*-means algorithm that regroups the similar windows into clusters. The analysis yielded dFNC measures such as the dwell time (i.e., the amount of time/scans a participant spent in each brain state).

sible solutions to open-ended problems (e.g., drawing several different sketches based on a given prompt). In this study, convergent thinking was measured using the standardized non-verbal task from The Evaluation of Potential Creativity (EpoC) battery (Lubart et al., 2011). The child was asked to create a drawing integrating at least three out of eight abstract shapes (e.g., an oval, a triangle, or a square) within 10 min. Instructions emphasized the creative thinking process (i.e., "Be as creative as possible!"). Each drawing was blindly rated on a scale ranging from one (low creative) to seven (high creative) by three trained raters. The criteria were based on the integration of shapes, originality of the final drawing, and storytelling. Inter-rater reliability was assessed as good (74%) by three independent raters, as measured from the percent agreement for multiple raters. Three different combinations were possible for each drawing between the raters (i.e., R1/R2, R1/R3, R2/R3). If two raters shared the same score, they received 1 point and 0 point if the score differs. Each drawing had a maximum of 3 points. The percentage of agreement was calculated by using the sum and dividing it by the total of combinations.

Statistical analyses were performed on convergent thinking scores to test for a statistical difference between Montessori-schooled children and traditionally-schooled children using a *t*-test.

2.4 | fMRI data acquisition

Anatomical and functional data (Figure 1a) was acquired at the Biomedical Imaging Center (CIBM-CHUV) of the University Hospital of Lausanne on a 3T PrismaFit MR scanner equipped with a 64-channel head-coil (Siemens Healthineers, VE11E Software version, Erlangen, Germany). For each subject, anatomical data was acquired using a MPRAGE (Magnetization Prepared – RApid Gradient Echo) 3-dimensional high-resolution isotropic T1-weighted sequence (TR = 2000 ms; TE = 2.47 ms; 208 slices; voxel size = $1 \times 1 \times 1$ mm; flip angle = 8°). This sequence served as a basis for brain segmentation and surface reconstruction. Functional data were acquired using a standard echo-planar gradient echo sequence combined with a simultaneous multi-slice (SMS) imaging technique to optimize the temporal resolution. Functional acquisition covered the whole brain (GRE $2.2 \times 2.2 \times 3$ mm, TR = 500 ms; TE = 33 ms; 48 axial slices; slice thickness = 2.6 mm; 10% gap between slices; flip angle = 47°; field of view [FOV] = 224 mm; SMS acceleration factor = 8). One acquisition session lasted 6 min for 720 volumes recorded. To avoid noise discomfort, earplugs were given to the participant, and to minimize head motion, foam pads were placed around the ears.

2.5 | Preprocessing fMRI data

All imaging data were preprocessed with fMRIPrep 20.2.1 (Esteban et al., 2019) (Figure 1b), which is based on Nipype 1.5.1 (Gorgolewski et al., 2011) (see Supplementary A). The main steps of the pipeline consist of aligning anatomical images with a brain atlas (MNI152NLin2009cAsym) for spatial normalization, brain tissue segmentation, and surface reconstruction. At the same time, functional data are preprocessed to generate brain masks and estimate head motion. Finally, functional images are coregistered with anatomical images to better define anatomical locations of the results by superposing and visualizing them on a high-resolution brain image.

Visual inspections pre- and post-data preprocessing were done by two independent researchers. Data were preprocessed using the automatic removal of motion artifacts using independent component analysis correction (AROMA), meant to improve movement correction. Then, frame-wise displacement (FD) and the spatial standard deviation of successive difference images (DVARS) metrics were used as strict exclusion criteria (mean lower than 1.4).

2.6 | Independent component analysis

An independent component analysis (ICA) was performed on the resting-state fMRI data using the GIFT toolbox on Matlab (Calhoun et al., 2001, https://trendscenter.org/software/gift/) (Figure 1c). First, to identify functional connectivity networks, the whole-brain voxel activity was divided into 100 independent components (ICs) based on previous studies in the field (Damaraju et al., 2014, 2020; Li et al., 2017). Second, to ensure the reliability of the independent components, an Infomax ICA was run 20 times with ICASSO (Himberg et al., 2004; http://www.cis.hut.fi/projects/ica/icasso). Third, a back-reconstruction was performed to estimate each subject's spatial maps and time courses using the GICA3 algorithm (Calhoun et al., 2001). Finally, additional post-processing steps were performed on the time courses to remove noise components. These steps consisted of (1) detrending linear, quadratic, and cubic trends, (2) performing multiple regressions on head motion, (3) removing detected outliers, and (4) applying low pass filtering with a 0.15 Hz cutoff.

2.7 | Networks of interest

Based on previous work in the field (Beaty et al., 2016; Beaty, Chen et al., 2018; Beaty, Kenett et al., 2018), we identified three networks of interest associated with creative thinking: the DMN, ECN, and SN. For the DMN, a total of six independent components were identified. For the ECN, three independent components were identified. For the SN, a total of five independent components were identified. The ICs were first identified by visual inspection and then confirmed using a correlation with a template retrieved from the Neurosynth platform (https://neurosynth.org/).

2.8 | Static functional network connectivity

To investigate the relationship between the three networks of interest, static functional network connectivity (sFNC) analysis was performed (Figure 1d). This analysis is based on the average connectivity of the participant's time courses in each ICs across the resting-state duration.

Furthermore, to evaluate the impact of age, pedagogy, and creative thinking on these functional networks of interest, we performed a multivariate analysis of the covariance (MANCOVA) (Allen et al., 2011) with age, pedagogy, and creative thinking as covariates. To investigate possible interactions effects, age X creative thinking, pedagogy X creative thinking, and pedagogy X age were also included in the model. The *p*-value significance threshold was set to 0.5. Then, the parameters for the *t*-threshold of the spatial maps, the *p*-threshold for univariate tests, and the low and high-frequency limits to computing fractional amplitude of low-frequency fluctuations (fALFF) were set to 1.0, 0.5, and 0.1–0.15 Hz, respectively. For the univariate results, a false discovery rate (FDR) correction was applied, and the threshold was set to 0.5.

Multivariate and univariate tests were performed and generated multiple features such as spatial maps, time courses spectra, and functional network connectivity (FNC) correlations. Here, a spatial map is a mask of the connectivity strength in each IC; the voxels selected for the spatial map are the ones that show a strong activation across all the subjects. A time-course spectrum provides an overview of the activity fluctuation across the resting state within an IC. A functional network connectivity (FNC) correlation is a matrix that displays the temporal correlation between the selected ICs.

2.9 | Dynamic functional network connectivity

Dynamic functional network connectivity (dFNC) was performed to explore how the networks of interest interact across the entirety of the resting-state scan (Figure 1e). For this analysis, we used a sliding window approach, based on each participant's resting-state time courses. The participants' time courses were divided into small segments of the same length. Based on past work (Beaty, Chen et al., 2018) a window length of 30 TRs with a Gaussian of $\sigma = 3$ TRs was applied. A new window started every 1 TR from the previous one, generating a total of 690 windows. Each window was an NxN correlation matrix with N corresponding to the independent components selected during the ICA.

The correlation matrices generated can occur several times in each participant across the resting state and all participants. A k-means algorithm was used to regroup the windows into clusters or "states," i.e., recurring correlational patterns between the networks of interest. The number of clusters was set to $k = 5$ (Allen et al., 2014). The algorithm used the city distance functionality with 150 iterations. The dFNC produced five different states, which were then evaluated through several metrics to compare state-wise differences between participants: the

TABLE 1 Demographics for the Montessori and traditional schooling groups.

Demographics and group variables	Montessori	Traditional	Statistical tests
N (F)	37 (19)	38 (24)	χ^2 (1, *N* = 75) = 1.61, *p* = 0.20
Age (SD)	9.69 (2.79)	9.98 (2.49)	*t*(73) = −0.49, *p* = 0.63
Age range	4.60–18.00	5.20–15.20	
Fluid intelligence	32.10 (4.46)	32.60 (6.17)	*t*(72) = −0.51, *p* = 0.61
Interest for pedagogy	2.70 (0.52)	2.51 (0.69)	*t*(72) = 1.33, *p* = 0.19
Parental style	3.19 (0.43)	3.38 (0.40)	*t*(72) = −1.95, *p* = 0.06
SES	3.04 (0.50)	3.02 (0.63)	*t*(72) = 0.18, *p* = 0.86

dwell time (the average time spent in each state), the number of states (i.e., the count of the different states encountered during the scan), the number of transitions (i.e., count of state switches), and the distance traveled (i.e., the sum of the distance between the different states). Finally, group statistics (two-sample t-tests) were performed on these measures to compare children in terms of the pedagogy (Montessori versus traditional) as there were no significant results in the sFNC analysis for age and creative thinking.

3 | RESULTS

To verify homogeneity between our groups with respect to intelligence and demographic variables, statistical analyses were performed, and the results are shown in Table 1. No group difference was observed between children from the two pedagogical approaches for age ($t(73) = -0.49$, $p = 0.63$). A nonsignificant trend was found for parental style ($t(72) = -1.95$, $p = 0.06$) in favor of traditionally-schooled children ($M = 3.38$, $SD = 0.40$) over Montessori-schooled children ($M = 3.19$, $SD = 0.43$). Furthermore, Mann-Whitney U tests showed no group difference on fluid intelligence ($U = 661$, $p = 0.80$), interest for pedagogy ($U = 598$, $p = 0.26$), and SES ($U = 680$, $p = 0.96$). Finally, the Chi-square test showed no difference in gender ratio (χ^2 (1, N = 75) = 1.61, $p = 0.20$). Therefore, as expected, these statistical analyses revealed comparable and homogenous groups in terms of intelligence, as well as home and parental environments.

3.1 | Creative thinking task

The Student's *t*-test showed a significant mean difference between the two groups ($t(73) = 3.96$, $p < 0.001$). Corroborating previous work (Besançon & Lubart, 2007; Denervaud et al., 2019; Lillard & Else-Quest, 2006), Montessori-schooled children scored on average higher ($M = 4.92$, $SD = 1.64$; Figure 2a) in convergent thinking than traditionally schooled children ($M = 3.46$, $SD = 1.57$).

Adding age as a covariate reveals an overall developmental increase in creative thinking ($F(1,72) = 19.05$, $p < 0.001$; Figure 2b).

3.2 | Group independent component analysis

Next, we examined functional brain networks across the entire sample of students using ICA. The ICA revealed canonical resting-state networks, including the DMN, ECN, and SN. Based on previous work, 14 components were selected as part of the networks of interest (Menon, 2011; Menon & Uddin, 2010; Supekar et al., 2010). For the DMN, components represented the left angular gyrus (lAG), the right angular gyrus (rAG), the posterior cingulate cortex (PCC), and the medial prefrontal cortex (mPFC). For the ECN, components represented the right and left dorsolateral prefrontal cortex (DLPFC) and the posterior parietal (PP) regions. For the SN, components represented the left anterior insula (lAI), the right anterior insula (rAI), and the anterior cingulate cortex (ACC).

3.3 | Static functional network connectivity

Our group-level analysis began by computing correlations between the networks of interest, allowing us to compare the pattern of correlation with existing literature (Figure 3). We found positive within-network correlations for the ICs composing the DMN (0.80) and the SN (0.38), as well as between DMN-ECN (0.25) and ECN-SN (0.34). A slight anti-correlation was observed between DMN-SN (−0.02). However, no correlation or anti-correlation was found within the ECN (0.00).

The effects of age, creative thinking, pedagogy, and their interaction terms on the independent components were evaluated using a MANCOVA. After FDR correction, there were no significant results for age and creative thinking. However, there was a significant result for pedagogy which was increased functional connectivity within the SN of traditionally-schooled children over Montessori-schooled children ($T = 2.73$, $p = 0.01$; Supplementary B).

3.4 | Dynamic functional network connectivity

We then assessed patterns of dFNC across the full sample of students. The sliding window approach was used to determine the dFNC of each

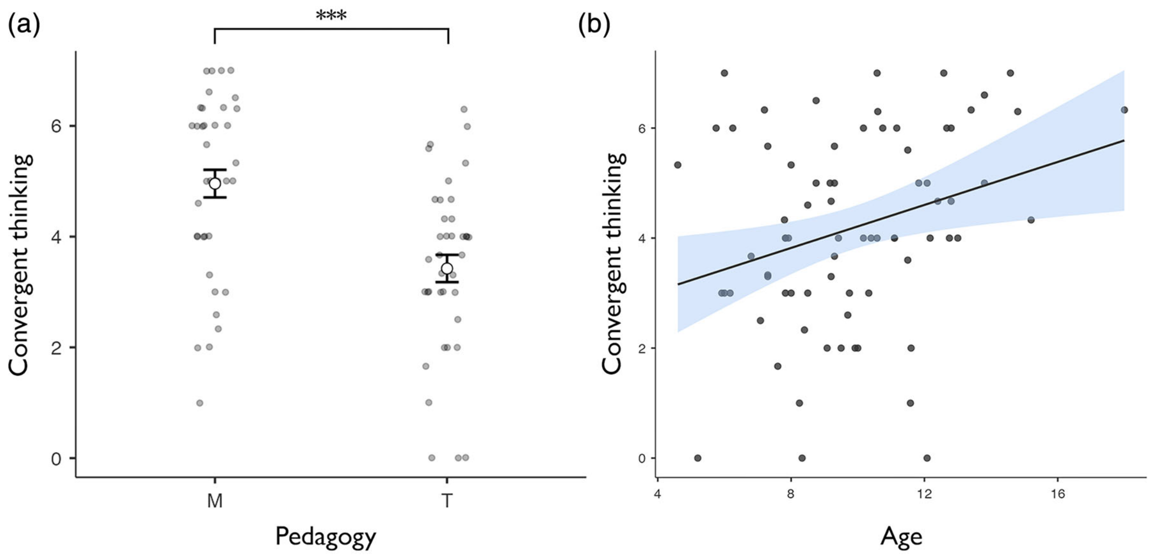

FIGURE 2 (a) Raw data of the results from the statistical analyses conducted on convergent thinking. M = Montessori-schooled children; T = traditionally-schooled children (*** $p < 0.001$). (b) Effect of age on convergent thinking.

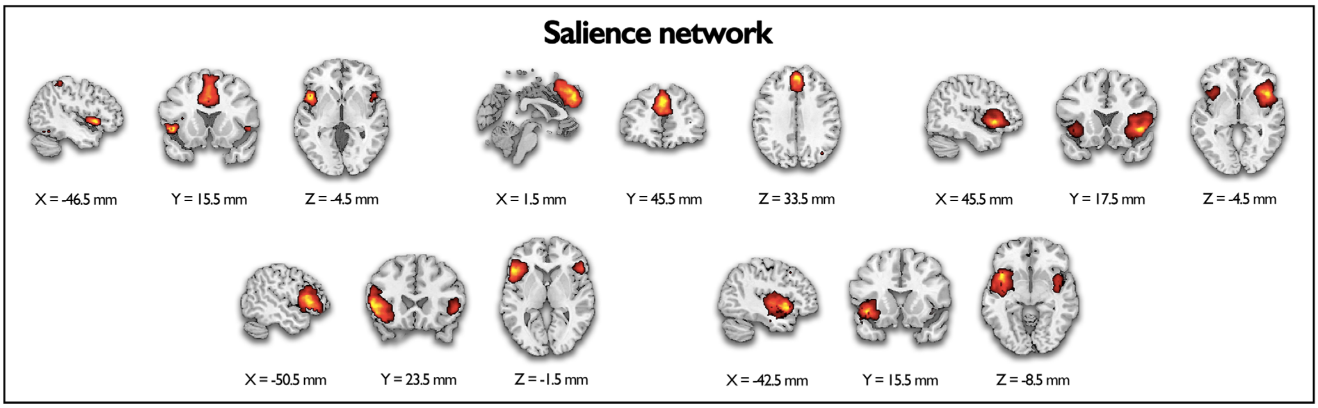

FIGURE 3 Independent components representing the SN.

subject between the three brain functional networks of interest (i.e., DMN, ECN, SN).

The dFNC was performed comparing children from the two pedagogies as it was the only significant effect in the sFNC analysis. Functional connectivity patterns occur multiple times in each subject, as well as between subjects, and k-means was used to separate the patterns into 5 distinct clusters or "states." The five different states are presented in Figure 4.

The first state is characterized by positive functional connectivity between all three brain networks of interest, a pattern previously linked to creative thinking (Beaty, Kenett et al., 2018). The second state shows higher intra-network functional connectivity in the DMN and the ECN as well as higher inter-network functional connectivity between the DMN and the ECN, concomitant with an anti-correlation between those networks and the SN. The third state shows high intra-network functional connectivity within the DMN, consistent with introspective cognitive processes (Andrews-Hanna, 2012). The fourth state was previously associated with a transition pattern revealing a metastable neural activity (Deco et al., 2017), characterized by no strong correlation between the networks and slight intra-network connectivity in the DMN and the ECN. The fifth state corresponds to a control-related pattern with intra-network functional connectivity in the SN, as well as inter-network functional connectivity between the ECN and the SN (Figure 4).

For each subject, the time spent in each state was computed as the mean dwell time. An ANOVA was computed to test whether the time spent in each state differed between the two groups. Furthermore, two sample *t*-tests were conducted to compare the mean dwell time, the number of states, the number of transitions, and the distance traveled between each state between Montessori- and traditionally-schooled children.

Among all states in the dfNC analysis, one effect emerged for pedagogy on the dwell time spent in state 3 (Figure 5). This occurred in the "introspective pattern" ($T = 2.73$, $p = 0.01$), that is, high intra-DMN

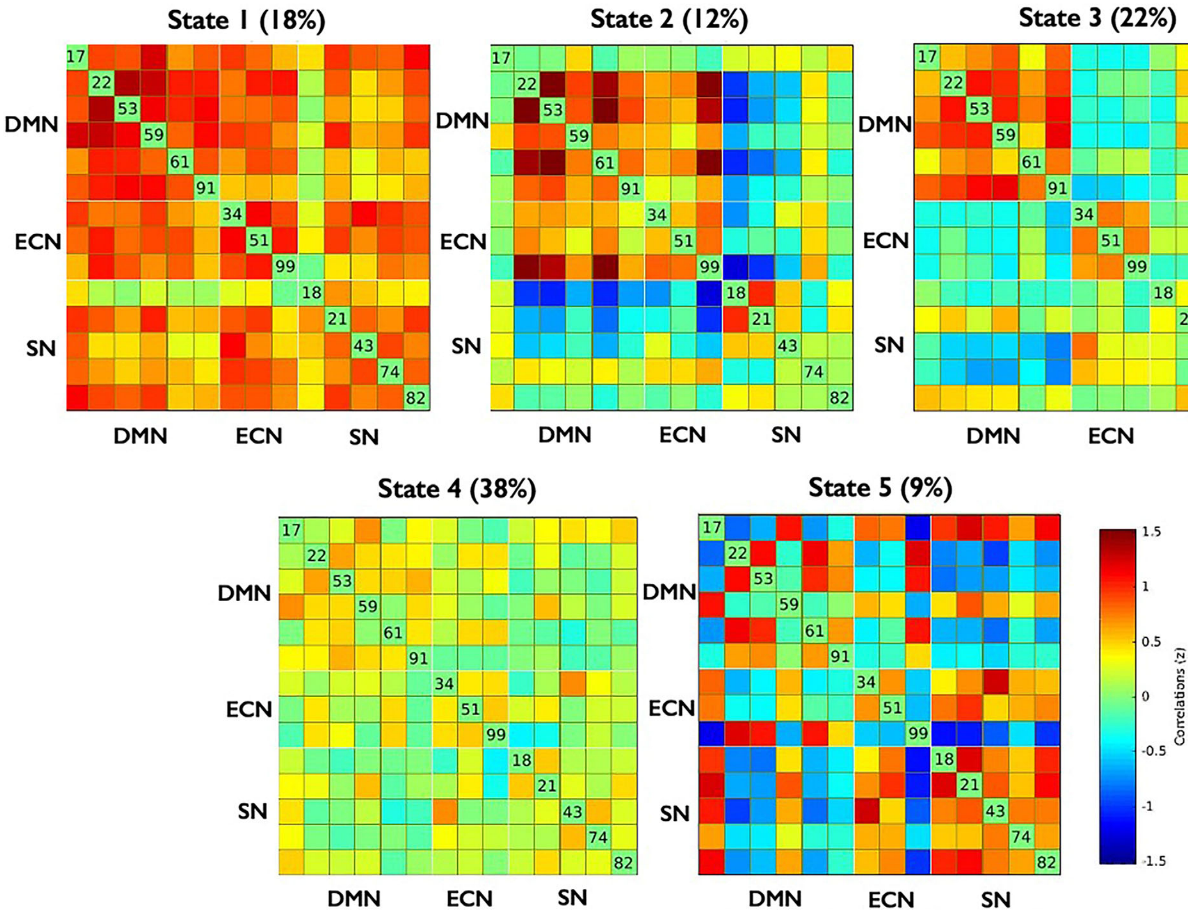

FIGURE 4 The five distinct states generated from the sliding window approach. Above each state, the amount of time spent in that state is reported (%). DMN = default mode network; ECN = executive control network; SN = salience network. Numbers on the diagonal represent the selected component out of the 100 included for each network.

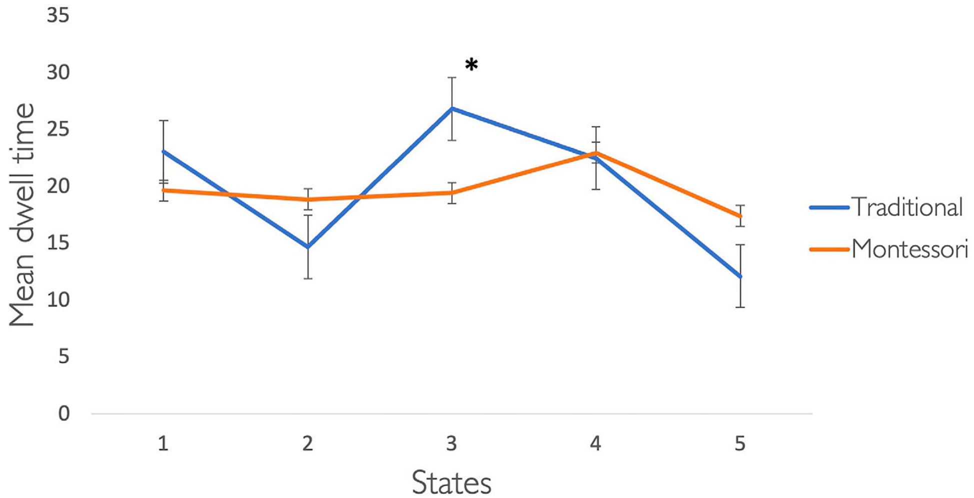

FIGURE 5 Mean dwell time across the five states for the traditionally-schooled children (blue), and the Montessori-schooled children (orange). The statistical comparison reveals steady dwell time amongst states in Montessori-schooled children, traditionally-schooled children's dwell time varies significantly. Furthermore, they spend more time in state 3 (i.e., high intra-DMN connectivity) than their peers from Montessori schools (* $p < 0.05$).

connectivity, where traditionally-schooled children showed an increased dwell time ($M = 26.82$, $SD = 11.93$) compared to Montessori-schooled children ($M = 19.42$, $SD = 11.53$). Interestingly, upon inspection of Figure 5, we can observe that Montessori-schooled children's dwell times are quite stable across states compared to traditionally-schooled children. To test this observation, a group-wise ANOVA was used to compare the effect of the states for each pedagogy. This analysis showed a main effect of the interaction between the states and pedagogy ($F(1,4) = 2.95$, $p < 0.021$): the dwell times of Montessori-schooled children showed no difference, while the dwell times of traditionally-schooled children differed significantly, suggesting that they tend to spend more time in different brain states than Montessori students.

Finally, no group differences were observed in terms of the number of states ($p = 0.56$), the number of transitions ($p = 0.88$), and the distance traveled ($p = 0.76$) between traditionally-schooled children and Montessori-schooled children.

In sum, the dynamic connectivity analysis extended the static connectivity analysis—which showed stronger connectivity within the SN of traditionally-schooled children—by additionally revealing stronger connectivity within the DMN of traditionally-schooled children, compared to Montessori-schooled children.

4 | DISCUSSION

Creativity has been highlighted as a key 21st-century key competency (Davies et al., 2017), raising questions about how creativity develops and how it can be nurtured in schools (Denervaud et al., 2019; Lillard & Else-Quest, 2006; Lubart et al., 2011). Studies have well-characterized brain functional connectivity underlying creative outcomes in adults, particularly within the DMN, SN, and ECN (Beaty, Chen et al., 2018; Li et al., 2017), yet developmental trajectories and effects of school pedagogy on brain networks relevant for creative thinking have remained unknown. The present study constitutes the first network neuroscience investigation to examine links between age, creative thinking, and school pedagogy. While Montessori-schooled children consistently scored higher on a creativity task, we found that traditionally-schooled children had an increased intra-SN functional connectivity, and they spent more time in an "introspective" pattern (intra-DMN activity). Together, these results suggest a modulatory effect of pedagogy on SN, a pivotal switch of cognitive flexibility, known to be systematically implicated in creative thinking processes.

The static functional connectivity analysis revealed a single significant effect of pedagogy. Notably, we found no independent effects of age and creative thinking on static connectivity. This is quite intriguing as increased or decreased functional connectivity between the networks of interest should be expected when children grow up or become more creative. Thus, age may be less sensitive to changes occurring between the three networks of interest. Another possible explanation may be that for children, other networks are more relevant than the three we examined here (DMN, ECN, and SN), which should be studied in future work.

Previous work has shown that Montessori-schooled children show higher creative thinking abilities than traditionally-schooled children (Besançon & Lubart, 2007; Denervaud et al., 2019; Eon Duval et al., 2022; Lillard & Else-Quest, 2006), a finding that we replicated here, suggesting how pedagogy may impact creative abilities. Montessori schools tend to follow the dynamic changes in creative thinking across the development (Eon Duval et al., 2022). First, children undertake associative learning tasks (Denervaud et al., 2021), and later only, explorative tasks are encouraged, a learning strategy that may consolidate their creative abilities (Eon Duval et al., 2022). These distinct steps in the learning process across development could be one reason why Montessori-schooled children show higher creative thinking skills than their peers from traditional schools, though this claim requires further investigation in future work.

The static functional connectivity analysis revealed that traditionally-schooled children show increased intra-SN functional connectivity than Montessori-schooled children. This strengthening could mean that, as the SN develops, its switching function with the DMN and the ECN may be different in traditionally-schooled children (Menon & Uddin, 2010). Thus, intra-SN functional connectivity may lead to a decrease in the DMN-ECN interaction and impact the development of creative thinking abilities. Previous work comparing traditionally-schooled children with Montessori-schooled children reported differences in ACC connectivity (sub-region of the SN), related to error-monitoring (i.e., facing unexpected events; Denervaud et al., 2020), as well as more flexibility in semantic memory organization (Denervaud et al., 2021). It may be that competitive settings induced by same-age children—in an adult-directed manner over similar activities and in preparation for a test—over-recruit the SN (i.e., too much information is perceived as salient at a time). Conversely, Montessori-schooled children spend more time in self-directed activities, discussing work with peers without time limits, to gain understanding (with no formal grades). This perspective corroborates previous work on cognitive flexibility presenting the SN as a switching hub, regulating DMN-ECN activity (Menon & Uddin, 2010). Hyperactivity from the SN consistently affects cognitive flexibility (Uddin, 2021), and perhaps by extension, creative thinking as well.

Finally, the dFNC showed that traditionally-schooled children spent more time in an "introspective" brain state which is characterized by increased intra-DMN activity. In terms of creative thinking, the DMN is thought to be involved in the early stages of idea generation, drawing on prior knowledge and experiences (Beaty et al., 2016). Also, the DMN is highly implicated in self-related and social cognition, memory retrieval, and experience (Ekhtiari et al., 2016). Our results suggest that traditionally-schooled children, compared to Montessori-schooled children, may over-engage the DMN, which is active in creative cognition, potentially limiting their ideas in the DMN, with less communication to control-related areas necessary for idea evaluation. This could be interpreted as a reason why lower creativity scores in traditionally-schooled children may be related to a dynamic functional imbalance (i.e., spending too much time in an introspective state rather than in executive modes).

In addition, the traditionally-schooled children showed significant differences between states compared to Montessori-schooled children suggesting less network stability when engaging in a specific task.

Importantly, our conclusions are based on resting-state data and thus remain speculative. Task-based research is needed to understand the extent to which an increased intra-DMN activity in traditionally-schooled children may hinder their creative performance. Curiously, Montessori-schooled children seem to spend time in different states in a more stable manner than traditionally-schooled children, which may reflect a better ability to switch from state to state.

Taken together, our study suggests less creativity-related brain network fluidity in traditionally-schooled children, potentially due to the strengthening of their SN over other networks such as the ECN and the DMN. We tentatively speculate that the ideas of traditionally-schooled children (generated by the DMN) could be less effectively forwarded to the ECN, which can in turn explain why traditionally-schooled children spent more time in an introspective pattern.

Several limitations need to be acknowledged and addressed in future work. First, the Montessori-schooled children participating in this study came from private schools, while the traditionally-schooled children came from public schools. To control for the selection bias as much as possible, we collected extensive information about cognitive abilities and family environments. Surprisingly, traditionally-schooled children tended to have a more enriched home environment than their peers from Montessori schools. However, we must note that the traditionally-schooled children recruited had parents showing a great interest in education and pedagogy. Nevertheless, other factors can influence the findings, such as parental level of creativity or curiosity and motivation in daily life. It may be that more creative parents seek alternative modes of education; they may be more open to new experiences and curious. Future work should include these variables to better study creativity development. Moreover, based on multiple studies consistently reporting an effect of pedagogy on creative thinking (e.g., Denervaud et al., 2019), even in randomized experimental settings (e.g., Lillard & Else-Quest, 2006), or compared with other alternative schooling pedagogies (e.g., Besançon & Lubart, 2007), we believe that school experience influences creative abilities beyond genetics (i.e., passed on from parents).

Also, we assessed convergent thinking through a drawing-based task, and verbal creativity was not considered. It is unknown whether verbal convergent thinking would similarly impact functional connectivity as we found for drawing-based creativity. However, we ran a pilot verbal task that revealed important difficulties for younger children due to less developed linguistic and abstract abilities compared to older children. Despite these limitations, our findings align with the current knowledge of creative thinking, particularly concerning the network neuroscience literature. We hope our cross-sectional results will be complemented with longitudinal data, which is a critical next step for future research.

This study unveils the important role of the SN in the creative thinking process across development and its susceptibility to school experience (i.e., pedagogy). The past decade has emphasized executive function skills, especially in current traditional schools (i.e., improving executive activities like homework, learning by heart, or testing). However, our study reveals that the SN has more importance and susceptibility across the schoolyears for creative cognition. Therefore, we suggest that educational practices target self-related experience (i.e., hands-on, interdisciplinary activities) and social diversity instead of executive tasks to support SN functional development. Such an approach exists already in the Montessori pedagogy, where cooperation and self-exploration are prioritized within highly diverse social settings. This approach seems to successfully nurture creative thinking at the behavioral and brain levels. We hope this work will emulate more work in that direction, as it has raised many new questions to be explored.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Raw data cannot be shared; however, functional connectivity of the selected brain networks can be shared upon request to the authors.

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SUPPORTING INFORMATION

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