The interplay of age and pedagogy in maturation of error-monitoring

Solange Denervaud^{1,2}, David A. Tovar³, Jean-François Knebel^{1,2}, Emeline Mullier⁴, Yasser Alemán-Gómez^{4,5}, Patric Hagmann^{4*}, & Micah M. Murray^{1,2,3,6*}

¹The Laboratory for Investigative Neurophysiology (The LINE), Department of Radiology, Lausanne University Hospital and University of Lausanne, 1011 Lausanne, Switzerland

²CIBM Center for Biomedical Imaging, Lausanne, Switzerland

³Vanderbilt Brain Institute, Vanderbilt University, Nashville, TN, USA

⁴Connectomics Lab, Department of Radiology, Lausanne University Hospital and University of Lausanne, 1011 Lausanne, Switzerland

⁵Center for Psychiatric Neuroscience, Department of Psychiatry, Lausanne University Hospital and University of Lausanne, Prilly, Switzerland.

⁶Department of Ophthalmology, Fondation Asile des aveugles and University of Lausanne, Switzerland

Abstract

Error monitoring allows us to adapt to an inherently dynamic environment, and relies mainly on the anterior cingulate cortex (ACC). Its protracted maturation suggests a window for experience-dependent plasticity. To investigate this possibility, we measured error-related response-locked potentials components with morphometric magnetic resonance imaging (MRI) measures of the ACC in twenty-six schoolchildren, aged 6-12 years, enrolled in either a Montessori or a traditional curriculum. We show that the caudal ACC undergoes significant morphometric changes during this age range that relate to error detection ERP activity. Furthermore, pedagogy modulates source localization activity related to error detection within the caudal ACC amongst others. We provide early evidence for a window of opportunity regarding the acquisition of error monitoring, with implications for education.

Keywords: Self-monitoring – error monitoring – brain development – anterior cingulate cortex – experience-dependent plasticity – school pedagogy

The interplay of age and pedagogy in maturation of error-monitoring

To function well in contemporary society, children need to gain independence and flexibility. Central to these adaptive processes stands the error monitoring system, which detects unexpected outcomes and provides opportunity to swiftly adjust behaviors (Ullsperger, Danielmeier, & Jocham, 2014). Error monitoring strongly relies on the caudal subregion of the anterior cingulate cortex (cACC), a central hub of the salience network (Margulies et al., 2007). Functional maturation of the cACC mainly occurs from 6 to 12 years of age (Kelly et al., 2009). This maturation window suggests a possible sensitive in which incorrect responses are learned through experience-dependent plasticity. To address this possibility, the present study investigated the relationship between cortical thickness changes within ACC subregions and established error-related electroencephalographic (EEG) components in 6-12 year-old children experiencing different error monitoring styles at school.

Our routine behaviors rely on automatized actions with expected outcomes. However, these expectations are occasionally unmet and generate a mismatch between planned and actual outcomes, such as flipping a light switch without the light coming on. In these circumstances, the error monitoring system is triggered, signaling the type of adaptation required to compensate for the *unexpected event* (e.g., adversity, conflict, incorrect response). An optimal error monitoring system provides potential explanations: “Maybe the bulb needs changing”, and can facilitate putting them into action (Ullsperger et al., 2014).

There is no direct measure of error monitoring, but indirect informative markers have been widely studied and reported in the context of incorrect responses. At a behavioral level, studies have generally focused on reaction times (RTs), which are usually slower after incorrect compared to correct responses (referred to as *post-error slowing*; Notebaert et al., 2009). There is also a long history of EEG studies examining the time course of events following incorrect responses. Despite differences in the protocols used, as long as speed and

1 accuracy are emphasized, a similar sequence of brain components time-locked to the
2 behavioral response has been reported in adults (Ullsperger et al., 2014). The first is an early
3 frontocentral negativity (typically peaking 50-100ms post-response onset), dubbed the *error-*
4 *related negativity* (ERN; Ullsperger & Danielmeier, 2016). The second is a later and slower
5 response (~200-400ms post-response onset) with a more central scalp distribution, called the
6 *error positivity* (Pe). They are thought to reflect an early task-unspecific detection of need for
7 adjustments (ERN) and a later task-specific selective attention for orientation and learning
8 (Pe) or conscious evaluation (Ullsperger & Danielmeier, 2016). ERN and Pe together reflect a
9 built-in error-detection system (Elton, Band, & Falkenstein, 2000) of respectively, low-level
10 perceptual ability for fast detection of mismatch (Falkenstein, Hohnsbein, Hoormann, &
11 Blanke, 1991; Murphy, van Moort, & Nieuwenhuis, 2016) and for later top-down processes
12 of adaptation/evaluation (Falkenstein, 2000; Nieuwenhuis, Ridderinkhof, Blom, Band, &
13 Kok, 2001; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005). While these markers are well-
14 studied in adults, developmental data are currently more scarce and inconsistent.

15 Both components have been observed in preschoolers (Brooker, Buss, & Dennis, 2011).
16 For example, the ERN was recorded in children as young as 3-4 years old (Grammer,
17 Carrasco, Gehring, & Morrison, 2014; Smulders, Soetens, & van der Molen, 2016). The
18 capacity to detect behavioral errors seems to gain in efficiency with age. Indeed, many of the
19 pediatric studies on ERN report an increase in amplitude with age, reaching adult-like levels
20 at late adolescence (Tamnes, Walhovd, Torstveit, Sells, & Fjell, 2013). However, there is also
21 evidence that the trajectory of this maturation is non-linear and inconsistent across ERN and
22 Pe components (Tamnes et al., 2013). For example, there are reports of reduced ERN
23 amplitude during adolescence (between 10-13 y.o.), despite constant Pe amplitude. Such
24 fluctuations are thought to reflect protracted maturation of error monitoring within the

underlying brain structures, i.e., the cACC, and may be related to experience-dependent plasticity.

ACC maturation follows a caudal to rostral path, from birth to late adolescence, tightly related to the successive gain in self-monitoring abilities at the motor, cognitive and social-affective levels (Margulies et al., 2007; Posner & Rothbart, 2007; Posner, Rothbart, Sheese, & Tang, 2007). Error monitoring relies on the cACC. This region readily captures mismatches and in turn activates other networks to adapt behavior (e.g., medial frontal cortex; see Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011). The activity of the cACC undergoes significant changes during childhood from around 6 to 12 years of age (Kelly et al., 2009; Velanova, Wheeler, & Luna, 2008), raising the possibility that during these years, children learn to monitor themselves when facing unexpected events at the cognitive level, such as incorrect responses. Error monitoring development may thus be subject to environmental influences, through experience-dependent plasticity, such as learning strategies reinforced within schooling pedagogies.

Pedagogical approaches differ in how they teach children to learn from their incorrect responses. Traditional pedagogy primarily involves teacher-led curricula, where knowledge is evaluated through tests with quantitative assessments (i.e., grades), delayed feedback, as well as within an environment of peers from the same age. Instead, child-centered-constructivist pedagogies, such as the Montessori pedagogy, encourages a children-led trial-and-error approach to learning, where knowledge is self-evaluated or receives qualitative feedback, without grades, in an environment of peers mixed across different ages (Lillard, 2005; Marshall, 2017; Montessori, 1936). These different pedagogical approaches were recently reported to impact error monitoring abilities at the behavioral and neural level in Montessori children compared to traditionally-schooled children (Denervaud, Fornari, et al., 2020;

Denervaud, Hess, Sander, & Pourtois, 2020; Denervaud, Knebel, Immordino-Yang, & Hagmann, 2020).

So far, developmental studies focused on error monitoring characterization (i.e. specific features, etc.) or individual trait or state differences in healthy or clinical populations (anxiety, mindsets, obsessive-compulsive disorders, etc.). Inconsistencies in reported outcomes preclude establishing a clear developmental trajectory. Here, we evaluated cACC maturation through cortical thickness changes, brain components for incorrect versus correct responses (ERN and Pe) changes with age, and the extent to which pedagogy experienced at school modulates children's error monitoring biomarkers between 6 and 12 years of age.

Specifically, we hypothesized that (i) ACC maturation (i.e., cortical thinning; Gogtay et al., 2004) would occur mainly within its caudal subregion, based on previous studies (Kelly et al., 2009; Velanova et al., 2008); (ii) ERN would show changes with age and would relate to cACC cortical thinning (maturation of the error monitoring system), while not Pe; and (iii) experience-dependent plasticity would be observed according to the pedagogical experiences of the children. We expected to observe enhanced error monitoring biomarkers in Montessori-schooled children, compared to the traditionally-schooled children. Previous comparative studies (Montessori- versus traditionally-schooled children) reported younger error-detection and self-correction (Denervaud, Knebel, et al., 2020), greater and faster engagement with errors originating within the ACC (Denervaud et al., 2020), and better academic achievement (Denervaud, Knebel, Hagmann, & Gentaz, 2019), which may translate into stronger brain responses (Hirsh & Inzlicht, 2010).

Methods

The experiment was conducted in accordance with the Declaration of Helsinki. The experimental procedures were approved by University ethical committee.

Participants

Written parental consent was obtained for each child, and informed assent was provided by each participant. No child had a history of a neurological or psychiatric illness. At each session, children received a voucher of ~35 USD. In total, 31 children completed the experiment as part of a larger study, including neuroimaging and behavioral measures aimed at evaluating the impact of school environment on development. Selection criteria were age (5 to 14 y.o.) and schooling system (children had to be enrolled in a Montessori or traditional school system). Children with an error rate lower than 10% (N=3), technical difficulties with EEG recording (N=1), or dental brace interference with MRI recording (N=1) were removed from the study, leaving 26 children for the analyses (mean age $\pm$ SD = 8.9 $\pm$ 1.6 years; all right-handed with normal or corrected-to-normal vision). Of these 26 children, all participated in the aforementioned behavioral study on performance-monitoring (Denervaud, Knebel, et al., 2020), and 12 of them participated in the aforementioned error monitoring fMRI study (Denervaud et al., 2020). Thus, all of the EEG and anatomical MRI analyses are reported here for the first time.

Group variables

To explore the idea of experience-dependent plasticity through pedagogy, we accounted for the Montessori or traditional schooling background of the child. To control, as best as possible, for the selection bias of Montessori-schooled children from private school and children from traditional public schools, we collected information about children's fluid intelligence (Raven, Raven, & Court, 2003), trait anxiety (STAI-Y2; Spielberger & Vagg, 1984) and mindsets (implicit theories of intelligence; Blackwell, Trzesniewski, & Dweck, 2007). We additionally collected information about parental socio-economic status (Genoud, 2011), education style and environment at home through a tailor-made questionnaire. Details

of each questionnaire are provided in the supplementary materials. Demographic data were collected online post-recording.

MRI acquisition and processing

Structural imaging was collected at the X, on a Siemens 3T Prisma-Fit MR scanner, with a 64-channel head-coil. For each child, a 3-dimensional high-resolution isotropic T1-weighted sequence (MPRAGE) was acquired (TR = 2000ms, TE = 2.47 ms, 208 slices; voxel size= 1mm³, flip angle=8°, percent phase FOV = 100).

Individual T1-weighted images were processed using the FreeSurfer 6.0.0 software (<http://surfer.nmr.mgh.harvard.edu>), a widely-used open-source image processing software package. FreeSurfer's image processing steps include brain extraction, automated Talaraich transformation, subcortical structures parcellation and brain tissue segmentation into white and grey matter.

Once white matter, grey matter and cerebrospinal fluid volumes were generated, the white (grey/white interface) and grey (csf/grey interface) cortical surfaces were reconstructed with the methods described by Fischl and colleagues (Fischl et al., 2002; Fischl, Sereno, & Dale, 1999). Cortical parcellation in gyral-based ROIs were calculated according to the Desikan-Killiany cortical atlas (Desikan et al., 2006), which contains 34 cortical structures for each hemisphere. Mean cortical thickness for each brain region was calculated as the average distance between the cortical surfaces for all vertices belonging to that region.

The cortical thickness, which represents a direct measure of the amount of grey matter contained in cortical layers along the perpendicular direction to each point on the surface, was used as a brain maturation biomarker (Gogtay et al., 2004). Based on our a priori hypothesis, the rostral ACC, cACC, and posterior cingulate cortex (PCC) were selected as regions of interest (ROIs) for the further analyses.

EEG procedure and processing

To explore the effect of error monitoring in school-like procedures, children performed a speeded continuous recognition task, modified for children from Thelen et al. (2014). In this task, children were asked to press a key as fast and accurately as possible, differentiating initial (i.e., ‘new’) versus repeated (i.e., ‘old’) presentations of line drawings (see Figure S1). Initial and repeated presentations of an item were pseudo-randomized within a block of 160 trials. Each object was repeated only once within each experimental block (i.e. 80 drawings for 160 trials). Children performed four blocks (640 trials in total). The line drawings were taken from a standardized set (Snodgrass & Vanderwart, 1980) or obtained from an online library (dgl.microsoft.com). The experiment took place in a sound-attenuated chamber (MDL 102126E from Whisperroom Inc.), where children were seated centrally in front of a 20” LCD computer monitor that was located about 80cm away from them to produce a visual angle of $\sim 4^\circ$ for the line drawings. The task was designed and controlled by PsychoPy 3.0 (Peirce et al., 2019), and all behavioural data were recorded in conjunction with a serial response box (Psychology Software Tools, Inc.; www.pstnet.com).

Continuous EEG was acquired at 1024Hz through a 64-channel Biosemi ActiveTwo AD-box (<http://www.biosemi.com>) referenced to the common mode sense (CMS; active electrode) and grounded to the driven right leg (DRL; passive electrode), which functions as a feedback loop driving the average potential across the electrode montage to the amplifier zero.

Pre-processing and analyses were performed using both homemade python scripts using Anaconda distribution (Python Software Foundation. Python Language Reference, version 3.5); Matlab (Mathworks, Natick, MA, USA Version 7.13); and the Cartool freeware (Brunet et al. 2011). Data were first filtered with a 2nd order Butterworth filter (12dB/octave roll-off; 1.0Hz high-pass; 60Hz low-pass; 50Hz notch). The filters were computed linearly in both forward and backward directions to eliminate phase shifts. Then EEG epochs were time-

locked to the motor response and spanned 200ms pre-response and 500ms post-response. Epochs with amplitude deviations in excess of $\pm 100\mu\text{V}$ at any channel, except for those labeled as 'bad' due to poor electrode-skin contact or damage, were considered artifacts and were excluded. Data from 'bad' channels (mean electrodes $\pm\text{SD} = 2.04\pm 2.49$ channels) were interpolated using 3D splines (Perrin et al., 1987). Prior to group-averaging response-locked potentials were baseline-corrected (-200 to -100ms from the response).

Two error-related components were extracted: the ERN and the Pe. To extract these components a peak-to-peak analysis was performed between the pre-motor response periods (-100 to 0ms) and periods of interest of each component (ERN: 0-100ms and Pe: 250-450ms). Based on previous literature (e.g. Aarts, De Houwer, & Pourtois, 2013; Grammer et al., 2014; Meyer, Weinberg, Klein, & Hajcak, 2012) and confirmed through an exploratory searchlight decoding analysis (Etzel, Zacks, & Braver, 2013) (see Figure S2), we selected scalp locations (FCz and Cz) and the time period of interest (0-100ms and 250-450ms), respectively, for the ERN and Pe components.

Statistical Analyses

Statistical analyses were computed using R Computer Software.

Group variables

Multiple independent t-tests with a 95% confidence interval (CI) for the mean difference were run on the different control variable scores to statistically determine significant differences between the two groups of children (experiencing Montessori versus traditional pedagogy), with a false-rate discovery (FDR) p -value correction at $q=0.05$.

Effect of Age and Pedagogy on ACC cortical thickness

To investigate the maturation of the ACC cortical thickness, a multiple analysis of covariance (MANCOVA) was run on cortical thickness measures of the three ROIs as dependent variables: rostral ACC, caudal ACC, and PCC, with age as a covariate and group (experiencing Montessori versus traditional pedagogy) as a factor (with $\alpha < 0.05$). Given the effect of gender on cortical thickness (Gennatas et al., 2017), we included gender as a factor and its interaction with group.

Effect of Age and Pedagogy on ERN and Pe

First, independent t-tests were computed on accuracy and error rates, to statistically evaluate differences between Montessori and traditionally-schooled children. Second, a repeated-measures analysis of covariance (rmANCOVA) with response type (correct, incorrect) as the within-subject factor, pedagogy (Montessori, traditional) as the between-subjects factor, and age as a covariate, was run on reaction times (RTs) (with $\alpha < 0.05$).

Finally, to investigate the effect of age and pedagogy on ERN and Pe, rmANOVAs were conducted on the peak-to-peak data with response type (correct, incorrect) as the within-subjects factor, pedagogy (Montessori, traditional) as the between-subjects factor and age as a covariate (with $\alpha < 0.05$). Post-hoc Tukey tests were performed when appropriate.

Relation between ACC cortical thickness, ERN and Pe

We computed the difference between incorrect and correct peak-to-peak values for each error-related brain component (i.e., Δ ERN and Δ Pe). Multiple linear regression analyses were calculated to predict Δ ERN and Δ Pe based on the cortical thickness measures of the rostral ACC, the cACC and the PCC, the age, and the pedagogy.

Additionally, we applied the local auto-regressive average distributed linear inverse solution (LAURA; Grave de Peralta Menendez, Gonzalez Andino, Lantz, Michel, & Landis, 2001) to an average period around ± 10 ms around the ERN response-locked peaks. We visualize and statistically contrast the likely underlying sources with use of the software brain

template for 7.5-13.5 year-old children (provided by Cartool). Statistical analysis entailed the same mixed model design as above and was performed using STEN software (Knebel & Notter, 2012). A spatial extent criterion of at least 5 contiguous significant nodes ($p<0.05$) was applied. F-maps thresholds by significant points were displayed, after separating distinguished blobs.

Results

Group variables

The groups were comparable in terms of age, gender, fluid intelligence, trait anxiety, and mindsets (all $p>0.05$). Furthermore, parental SES, education style and environment at home were similar as well (Table 1).

Effect of Age and Pedagogy on ACC cortical thickness

Corroborating our hypothesis, the thickness of the cACC significantly decreased with age ($p=0.047$, Figure 1A), but not within the PCC ($p=0.292$), or the rACC ($p=0.186$). There was an effect of pedagogy on PCC cortical thickness ($p=0.018$), with the traditionally-schooled children showing thinner PCC (mean thickness $\pm$ SD = 5.51 ± 0.12 mm) compared to the Montessori-schooled children (mean thickness $\pm$ SD = 5.75 ± 0.33 mm). There was no gender-specific cortical thickness differences for the ROIs ($p>0.208$).

Effect of Age and Pedagogy on ERN and Pe

Overall, participants committed an average of 17.3% (SD=11.4%) errors, with an accuracy rate of 73.2% (SD=19.7%). Age was unrelated to accuracy, $r_{(26)}=-0.018$, $p=0.93$. Both error and accuracy rates were comparable between the Montessori and traditionally-schooled children (respectively $t_{(24)}=0.81$, $p=0.43$, Cohen's $d=0.32$ and $t_{(24)}=0.25$, $p=0.80$, Cohen's $d=0.10$). As shown in previous studies, participants were faster on incorrect than correct trials ($M_{RT}\pm$ SD = 915 ± 357 ms versus 1050 ± 442 ms; $F_{(1,23)}=6.37$, $p=0.019$, $\eta_p^2=0.22$). Furthermore, age had a significant effect on RT of both correct and incorrect trials

($F_{(1,23)}=19.74, p<.001, \eta_p^2=0.46$), with older children being faster. There was no evidence of a significant effect of pedagogy ($p=0.84$) nor of an interaction between pedagogy and RT ($p=0.64$). We obtained comparable behavioral outcomes in both groups.

For both groups of children, ERN peak-to-peak amplitude was significantly more negative on incorrect than correct trials ($-5.18 \pm 2.95 \mu V$ versus $-4.16 \pm 3.12 \mu V$; $F_{(1,23)}=6.69, p=0.016, \eta_p^2=0.23$, Figure 1B). There was a main effect of Pedagogy as well ($F_{(1,23)}=5.34, p=0.030, \eta_p^2=0.19$). Montessori-schooled children had overall more negative brain responses than traditionally-schooled children ($p_{\text{tukey}}=0.031$). There was a significant interaction of Response Type (correct, incorrect) on Age, $F_{(1,23)}=5.39, p=0.030, \eta_p^2=0.19$, with increased negativity for incorrect responses, while increased positivity for correct responses in younger children. The Pedagogy $\times$ Response Type interaction was not significant ($p>0.05$).

Analysis of the Pe peak-to-peak amplitude revealed a significant main effect of Response Type (correct, incorrect; $F_{(1,23)}=9.55, p=0.005, \eta_p^2=0.29$, Figure S3). There was also a significant interaction of Response Type (correct, incorrect) on Age, $F_{(1,23)}=5.74, p=0.025, \eta_p^2=0.20$, with increasing age related to higher positivity for correct responses, but not for incorrect responses.

Relation between ACC cortical thickness, ΔERN and ΔPe

Children's ΔERN was reliably predicted by Age ($F_{(1,20)}=8.77, p=0.008$) and cACC cortical thickness ($F_{(1,20)}=5.05, p=0.036$) (Figure 1C). Larger ΔERN were related to thicker cortical values. Neither pedagogy, nor PCC or rACC were predictors of ΔERN ($p=0.166$).

Children's ΔPe was reliably predicted by Age only ($F_{(1,20)}=4.36, p=0.050$), with older children showing smaller ΔPe . No other factor was found to be a significant predictor of ΔPe ($p>0.517$).

For the ERN, statistical analyses of distributed source estimations revealed significant interactions between Response Type and Pedagogy; within the left cACC and mPFC, and

1 within the left inferior temporal cortex and cerebellum (Figure 1D). Post-hoc t-tests revealed
2 higher ERN amplitudes for correct responses versus incorrect responses for Montessori versus
3 traditionally-schooled children.

4 **Discussion**

5 Error monitoring is central to flexible adaptation, and mainly relies on the
6 ACC. The current study investigated the extent to which cortical thickness changes
7 within subregions of the ACC were related to the EEG components of error
8 monitoring (i.e., Δ ERN and Δ Pe), and whether experience-dependent plasticity
9 through pedagogy (i.e., interaction) was observable.

10 Regarding the morphometric data, we report brain maturation (cortical
11 thinning) within the cACC that corroborates previous work showing functional
12 changes from around 6 to 12 years of age (Kelly et al., 2009; Velanova et al., 2008).
13 The cACC, together with bilateral insula, form the salience network (Menon & Uddin,
14 2010), which changes during these years (Uddin, Supekar, Ryali, & Menon, 2011).
15 The salience network is triggered for “oddball” events, such as incorrect responses. It
16 may be that children at that age are more sensitive to cognitive mismatches,
17 optimizing their error monitoring development plasticity. This attentional bias may
18 contribute to both early perceptive abilities, as reflected by the ERN peak, as well as in
19 feedback integration for adaptive processes, contributing to the observed Pe peak. We
20 also found thicker PCC in Montessori compared to traditionally-schooled children.
21 PCC is a central hub of the default mode network, often reported to be involved in
22 internally-directed and creative cognition (Beaty et al., 2014; Immordino-Yang,
23 Christodoulou, & Singh, 2012; Leech & Sharp, 2014; Raichle et al., 2001). Previous
24 work has shown an effect of Montessori pedagogy on creative abilities and mindful
25 thinking (Denervaud et al., 2019; Lillard & Else-Quest, 2006; Lillard, 2011; Rathunde,

2001). Future work will be necessary to investigate the extent to which default activity is modulated by pedagogy, and to shed light on this difference in morphology.

Both early and late response-locked EEG components, ERN and Pe, were observed to vary with age. However, amplitudes for correct and incorrect responses exhibited patterns suggesting that detection and regulation of correct versus incorrect responses may change across development. Correct versus incorrect responses were processed as more different in younger children than older children of our cohort (>9 yo.). Previous work reported stronger behavioral and brain activity for correct rather than incorrect responses in schoolchildren (Denervaud, Fornari, et al., 2020; van den Bos, Guroglu, van den Bulk, Rombouts, & Crone, 2009). Together these findings suggest a dynamic, likely non-linear, development of error monitoring with possible shift in incorrect versus correct processing of responses across age. It may be that correct responses (less frequent than errors) are first perceived as unexpected early in the learning curve, and not the other way around. This idea could explain inconsistencies reported in developmental studies (Tamnes et al., 2013). Future work should therefore look at correct and incorrect trials separately within a longitudinal framework.

Children enrolled in Montessori schools also exhibited a generally larger early brain response, for both correct and incorrect responses. Montessori curricula offer pedagogical tools in the form of self-corrective materials, so that children from early years onwards are trained to explore concepts through trial-and-error strategies, without evaluative feedback such as grades (Marshall, 2017; Montessori, 1936). This approach may reinforce their abilities to monitor response outcomes, independently of correct or incorrect actions.

Source estimations for Δ ERN confirmed differences in underlying active brain regions. Responses from Montessori and traditionally-schooled children differ in early stages of error monitoring (ERN) within the cACC and the mPFC. This is in close agreement with previous work on error or conflict-monitoring where the ACC is robustly activated (e.g.

Carter et al., 1998; Kiehl, Liddle, & Hopfinger, 2000; van Veen & Carter, 2002), and linked to greater prefrontal activity (Botvinick, Cohen, & Carter, 2004). Furthermore, differences within the left inferior temporal cortex and cerebellum may be related to post-response learning and memorizing processes (Becker et al., 2013; Keren-Happuch, Shen-Hsing, Moon-Ho, & Desmond, 2014; Marvel & Desmond, 2010). In the current study, Montessori-schooled children had stronger brain activity for correct rather than incorrect responses, while traditionally-schooled children showed the reverse pattern. It may thus be that early error signals are dissimilar in Montessori and traditional schoolchildren, corroborating recent behavioral and neural findings (Denervaud, Hess, Sander, & Pourtois, 2020; Denervaud, Fornari, et al., 2020). Future work should continue exploring this idea of a window of opportunity for error monitoring abilities, where experience could have significant impact.

Montessori versus traditionally-schooled children did not differ on demographic variables, nor on their task-related behavioral outcomes, minimizing contributions of a selection bias. However, we found some experience-dependent changes at the neural level, revealing that while subtle changes in fundamental competences occur, many behavioral measures cannot capture them. This observation encourages future work in the field of education to combine behavioral and neural measures, to better capture developmental changes in learning how to learn (Soderstrom & Bjork, 2015). To overcome some limitations of the current study, future work should include a larger sample size, and, optimally, use randomized designs.

Here, we show that while error monitoring and its underlying brain structure, the cACC, undergo major changes in 6- to 12-year-old children, there is a modulatory effect of pedagogy experienced. Given the impact of error monitoring on flexible adaptation later in life, this work calls for further research to unveil how error monitoring develops in the context

- 1 of school pedagogy, beyond behavioral measures, and raises the question of a possible
- 2 window of plasticity.

References

- Aarts, K., De Houwer, J., & Pourtois, G. (2013). Erroneous and correct actions have a different affective valence: evidence from ERPs. *Emotion, 13*(5), 960-973. doi:10.1037/a0032808
- Beaty, R. E., Benedek, M., Wilkins, R. W., Jauk, E., Fink, A., Silvia, P. J., . . . Neubauer, A. C. (2014). Creativity and the default network: A functional connectivity analysis of the creative brain at rest. *Neuropsychologia, 64*, 92-98. doi:10.1016/j.neuropsychologia.2014.09.019
- Blackwell, L. S., Trzesniewski, K. H., & Dweck, C. S. (2007). Implicit theories of intelligence predict achievement across an adolescent transition: a longitudinal study and an intervention. *Child Dev, 78*(1), 246-263. doi:10.1111/j.1467-8624.2007.00995.x
- Brooker, R. J., Buss, K. A., & Dennis, T. A. (2011). Error-monitoring brain activity is associated with affective behaviors in young children. *Dev Cogn Neurosci, 1*(2), 141-151. doi:10.1016/j.dcn.2010.12.002
- Carter, C. S., Braver, T., Barch, D. M., Botvinick, M., Noll, D., & Cohen, J. D. (1998). The role of the anterior cingulate cortex in error detection and the on-line monitoring of performance: An event related fMRI study. *Biological Psychiatry, 43*, 13s-13s. doi:10.1016/S0006-3223(98)90491-7
- Danielmeier, C., Eichele, T., Forstmann, B. U., Tittgemeyer, M., & Ullsperger, M. (2011). Posterior medial frontal cortex activity predicts post-error adaptations in task-related visual and motor areas. *J Neurosci, 31*(5), 1780-1789. doi:10.1523/JNEUROSCI.4299-10.2011
- Denervaud, S., Fornari, E., Yang, X.-F., Hagmann, P., Immordino-Yang, M. H., & Sander, D. (2020). An fMRI study of error monitoring in Montessori and traditionally-schooled children. *npj Science of Learning, 5*(1). doi:10.1038/s41539-020-0069-6
- Denervaud, S., Hess, A., Sander, D., & Pourtois, G. (2020). Children's automatic evaluation of self-generated actions is different from adults. *Dev Sci*, e13045. doi:10.1111/desc.13045
- Denervaud, S., Knebel, J. F., Hagmann, P., & Gentaz, E. (2019). Beyond executive functions, creativity skills benefit academic outcomes: Insights from Montessori education. *PLoS One, 14*(11), e0225319. doi:10.1371/journal.pone.0225319
- Denervaud, S., Knebel, J. F., Immordino-Yang, M. H., & Hagmann, P. (2020). Effects of Traditional Versus Montessori Schooling on 4- to 15-Year Old children's Performance Monitoring. *Mind Brain and Education*. doi:<https://doi.org/10.1111/mbe.12233>
- Desikan, R. S., Segonne, F., Fischl, B., Quinn, B. T., Dickerson, B. C., Blacker, D., . . . Killiany, R. J. (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage, 31*(3), 968-980. doi:10.1016/j.neuroimage.2006.01.021
- Elton, M., Band, G., & Falkenstein, M. (2000). To err is human. *Biological Psychology, 51*(2-3), 83-85. doi:10.1016/S0301-0511(99)00035-6
- Falkenstein, M. (2000). Action monitoring, evaluation, and control. *Psychophysiology, 37*, S9-S9.
- Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of Crossmodal Divided Attention on Late Erp Components .2. Error Processing in Choice Reaction Tasks. *Electroencephalography and Clinical Neurophysiology, 78*(6), 447-455. doi:10.1016/0013-4694(91)90062-9

- 1 Fischl, B., Salat, D. H., Busa, E., Albert, M., Dieterich, M., Haselgrove, C., . . . Dale, A. M.
2 (2002). Whole brain segmentation: automated labeling of neuroanatomical structures in
3 the human brain. *Neuron*, 33(3), 341-355. doi:S089662730200569X [pii]
- 4 Fischl, B., Sereno, M. I., & Dale, A. M. (1999). Cortical surface-based analysis. II: Inflation,
5 flattening, and a surface-based coordinate system. *Neuroimage.*, 9(2), 195-207.
- 6 Gennatas, E. D., Avants, B. B., Wolf, D. H., Satterthwaite, T. D., Ruparel, K., Ciric, R., . . .
7 Gur, R. C. (2017). Age-Related Effects and Sex Differences in Gray Matter Density,
8 Volume, Mass, and Cortical Thickness from Childhood to Young Adulthood. *J*
9 *Neurosci*, 37(20), 5065-5073. doi:10.1523/JNEUROSCI.3550-16.2017
- 10 Genoud, P. (2011). Indice de position socioéconomique (IPSE) : un calcul simplifié:.
- 11 Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., . . .
12 Thompson, P. M. (2004). Dynamic mapping of human cortical development during
13 childhood through early adulthood. *Proc Natl Acad Sci U S A*, 101(21), 8174-8179.
14 doi:10.1073/pnas.0402680101
- 15 Grammer, J. K., Carrasco, M., Gehring, W. J., & Morrison, F. J. (2014). Age-related changes
16 in error processing in young children: a school-based investigation. *Dev Cogn Neurosci*,
17 9, 93-105. doi:10.1016/j.dcn.2014.02.001
- 18 Hirsh, J. B., & Inzlicht, M. (2010). Error-related negativity predicts academic performance.
19 *Psychophysiology*, 47(1), 192-196. doi:10.1111/j.1469-8986.2009.00877.x
- 20 Hudson, L. N., Newbold, T., Contu, S., Hill, S. L., Lysenko, I., De Palma, A., . . . Purvis, A.
21 (2017). The database of the PREDICTS (Projecting Responses of Ecological Diversity
22 In Changing Terrestrial Systems) project. *Ecol Evol*, 7(1), 145-188.
23 doi:10.1002/ece3.2579
- 24 Immordino-Yang, M. H., Christodoulou, J. A., & Singh, V. (2012). Rest Is Not Idleness:
25 Implications of the Brain's Default Mode for Human Development and Education.
26 *Perspect Psychol Sci*, 7(4), 352-364. doi:10.1177/1745691612447308
- 27 Kelly, A. M., Di Martino, A., Uddin, L. Q., Shehzad, Z., Gee, D. G., Reiss, P. T., . . . Milham,
28 M. P. (2009). Development of anterior cingulate functional connectivity from late
29 childhood to early adulthood. *Cereb Cortex*, 19(3), 640-657.
30 doi:10.1093/cercor/bhn117
- 31 Kiehl, K. A., Liddle, P. F., & Hopfinger, J. B. (2000). Error processing and the rostral anterior
32 cingulate: An event-related fMRI study. *Psychophysiology*, 37(2), 216-223. doi:Doi
33 10.1017/S0048577200990231
- 34 Knebel, J.-F., & Notter, M. P. (2012). STEN 1.0: Statistical Toolbox for Electrical
35 Neuroimaging (Version 1.0). Zenodo. <http://doi.org/10.5281/zenodo.1167723>
- 36 Leech, R., & Sharp, D. J. (2014). The role of the posterior cingulate cortex in cognition and
37 disease. *Brain*, 137, 12-32. doi:10.1093/brain/awt162
- 38 Lillard, A., & Else-Quest, N. (2006). The early years. Evaluating Montessori education.
39 *Science*, 313(5795), 1893-1894. doi:10.1126/science.1132362
- 40 Lillard, A. S. (2005). *Montessori : the science behind the genius*. New York: Oxford University
41 Press.
- 42 Lillard, A. S. (2011). Mindfulness Practices in Education: Montessori's Approach.
43 *Mindfulness*, 2(2), 78-85. doi:10.1007/s12671-011-0045-6
- 44 Margulies, D. S., Kelly, A. M., Uddin, L. Q., Biswal, B. B., Castellanos, F. X., & Milham, M.
45 P. (2007). Mapping the functional connectivity of anterior cingulate cortex.
46 *Neuroimage*, 37(2), 579-588. doi:10.1016/j.neuroimage.2007.05.019
- 47 Marshall, C. (2017). Montessori education: a review of the evidence base. *npj Science of*
48 *Learning*, 2(1). doi:10.1038/s41539-017-0012-7

- 1 Menon, V., & Uddin, L. Q. (2010). Saliency, switching, attention and control: a network model
2 of insula function. *Brain Structure & Function*, 214(5-6), 655-667. doi:10.1007/s00429-
3 010-0262-0
- 4 Meyer, A., Weinberg, A., Klein, D. N., & Hajcak, G. (2012). The development of the error-
5 related negativity (ERN) and its relationship with anxiety: evidence from 8 to 13 year-
6 olds. *Dev Cogn Neurosci*, 2(1), 152-161. doi:10.1016/j.dcn.2011.09.005
- 7 Montessori, M. (1936). *The Secret of Childhood* (1981 ed.). New York: Ballantine.
- 8 Murphy, P. R., van Moort, M. L., & Nieuwenhuis, S. (2016). The Pupillary Orienting Response
9 Predicts Adaptive Behavioral Adjustment after Errors. *PLoS One*, 11(3), e0151763.
10 doi:10.1371/journal.pone.0151763
- 11 Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P., & Kok, A. (2001). Error-related
12 brain potentials are differentially related to awareness of response errors: evidence from
13 an antisaccade task. *Psychophysiology*, 38(5), 752-760.
- 14 Notebaert, W., Houtman, F., Opstal, F. V., Gevers, W., Fias, W., & Verguts, T. (2009). Post-
15 error slowing: an orienting account. *Cognition*, 111(2), 275-279.
16 doi:10.1016/j.cognition.2009.02.002
- 17 Overbeek, T. J. M., Nieuwenhuis, S., & Ridderinkhof, K. R. (2005). Dissociable components
18 of error processing - On the functional significance of the Pe Vis-a-vis the ERN/Ne.
19 *Journal of Psychophysiology*, 19(4), 319-329. doi:10.1027/0269-8803.19.4.319
- 20 Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Hochenberger, R., Sogo, H., . . . Lindelov,
21 J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behav Res Methods*.
22 doi:10.3758/s13428-018-01193-y
- 23 Posner, M. I., & Rothbart, M. K. (2007). *Educating the human brain* (1st ed.). Washington,
24 DC: American Psychological Association.
- 25 Posner, M. I., Rothbart, M. K., Sheese, B. E., & Tang, Y. (2007). The anterior cingulate gyrus
26 and the mechanism of self-regulation. *Cogn Affect Behav Neurosci*, 7(4), 391-395.
- 27 Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G.
28 L. (2001). A default mode of brain function. *Proc Natl Acad Sci U S A*, 98(2), 676-682.
29 doi:10.1073/pnas.98.2.676
- 30 Rathunde, K. (2001). Montessori Education and optimal experience: a framework for new
31 research. *The NAMTA Journal*, 26(1), 11-43.
- 32 Raven, J., Raven, J. C., & Court, J. H. (2003). Manual for Raven's Progressive Matrices and
33 Vocabulary Scales. Section 1: General Overview. . San Antonio, TX: Harcourt
34 Assessment.
- 35 Smulders, S. F., Soetens, E., & van der Molen, M. W. (2016). What happens when children
36 encounter an error? *Brain Cogn*, 104, 34-47. doi:10.1016/j.bandc.2016.02.004
- 37 Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: norms for name
38 agreement, image agreement, familiarity, and visual complexity. *J Exp Psychol Hum*
39 *Learn*, 6(2), 174-215. doi:10.1037//0278-7393.6.2.174
- 40 Soderstrom, N. C., & Bjork, R. A. (2015). Learning versus performance: an integrative review.
41 *Perspect Psychol Sci*, 10(2), 176-199. doi:10.1177/1745691615569000
- 42 Spielberger, C. D., & Vagg, P. R. (1984). Psychometric properties of the STAI: a reply to
43 Ramanaiah, Franzen, and Schill. *J Pers Assess*, 48(1), 95-97.
44 doi:10.1207/s15327752jpa4801_16
- 45 Sunil, M., Hieu, H. Q., Arjan Singh, R. S., Ponnampalavanar, S., Siew, K. S. W., & Loch, A.
46 (2019). Evolving trends in infective endocarditis in a developing country: a
47 consequence of medical progress? *Ann Clin Microbiol Antimicrob*, 18(1), 43.
48 doi:10.1186/s12941-019-0341-x

- 1 Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain : 3-*
2 *dimensional proportional system : an approach to cerebral imaging*. Stuttgart ; New
3 York: Georg Thieme.
- 4 Tamnes, C. K., Walhovd, K. B., Torstveit, M., Sells, V. T., & Fjell, A. M. (2013). Performance
5 monitoring in children and adolescents: a review of developmental changes in the error-
6 related negativity and brain maturation. *Dev Cogn Neurosci*, 6, 1-13.
7 doi:10.1016/j.dcn.2013.05.001
- 8 Uddin, L. Q., Supekar, K. S., Ryali, S., & Menon, V. (2011). Dynamic reconfiguration of
9 structural and functional connectivity across core neurocognitive brain networks with
10 development. *J Neurosci*, 31(50), 18578-18589. doi:10.1523/JNEUROSCI.4465-
11 11.2011
- 12 Ullsperger, M., & Danielmeier, C. (2016). Reducing Speed and Sight: How Adaptive Is Post-
13 Error Slowing? *Neuron*, 89(3), 430-432. doi:10.1016/j.neuron.2016.01.035
- 14 Ullsperger, M., Danielmeier, C., & Jocham, G. (2014). Neurophysiology of performance
15 monitoring and adaptive behavior. *Physiol Rev*, 94(1), 35-79.
16 doi:10.1152/physrev.00041.2012
- 17 van den Bos, W., Guroglu, B., van den Bulk, B. G., Rombouts, S. A. R. B., & Crone, E. A.
18 (2009). Better than expected or as bad as you thought? The neurocognitive development
19 of probabilistic feedback processing. *Frontiers in Human Neuroscience*, 3. doi:ARTN
20 52
21 10.3389/neuro.09.052.2009
- 22 van Veen, V., & Carter, C. S. (2002). The anterior cingulate as a conflict monitor: fMRI and
23 ERP studies. *Physiol Behav*, 77(4-5), 477-482.
- 24 Velanova, K., Wheeler, M. E., & Luna, B. (2008). Maturation Changes in Anterior Cingulate
25 and Frontoparietal Recruitment Support the Development of Error Processing and
26 Inhibitory Control. *Cerebral Cortex*, 18(11), 2505-2522. doi:10.1093/cercor/bhn012
27
28

1

2

3

4

Independent Samples T-Test					
	Mean (SD)		Statistic	<i>p</i>	Cohen's <i>d</i>
	Montessori	Traditional			
Age	8.82 (1.64)	8.74 (1.65)	0.04	<i>0.97</i>	0.02
PM-47	34.08 (2.35)	32.36 (3.27)	1.52	<i>0.14</i>	0.60
Anxiety	13.67 (6.39)	13.14 (4.88)	0.24	<i>0.82</i>	0.09
Mindset	13.46 (6.19)	15.62 (4.99)	-1.54	<i>0.14</i>	0.63
SSE	7.18 (0.87)	7.50 (1.24)	-0.72	<i>0.48</i>	0.29
Parental Style (score)	26.82 (4.53)	26.86 (4.15)	-0.02	<i>0.98</i>	0.01

5 **Table 1 Demographic variables**

6

7

A. Cortical changes from 6 to 12 yo.

B. Error-Related Negativity (ERN)

C. cACC and ERN relationship

D. Modulation by school experience (ERN)

Source estimation, $\alpha < 0.05$

Figure 1 Effects of Age and pedagogy on the cACC maturation and the ERN. A. Cortical Thickness within the ACC: effect of age on the caudal sub-region of the anterior cingulate cortex that is significantly thinner across 6 to 12 years of age ($p < 0.047$). **B. ERN (incorrect-correct) component** as measured at FCz through Peak-to-Peak analyses **C. ERN was found to be a significant predictor of cACC thickness** ($p < 0.036$). **D. ERN source estimation across the Montessori and traditionally-schooled children**, interactions found within the cACC ($\alpha < 0.05$), among others (mPFC, left inferior temporal gyrus and cerebellum).