Effects of traditional versus Montessori schooling on 4 to 15-year old children's performance monitoring

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ABSTRACT

Through performance monitoring individuals detect and learn from unexpected outcomes, indexed by post-error slowing and post-error improvement in accuracy. Though performance monitoring is essential for academic learning and improves across childhood, its susceptibility to educational influences has not been studied. Here we compared performance monitoring on a flanker task in 234 children aged 4 through 15, from traditional or Montessori classrooms. While traditional classrooms emphasize that students learn from teachers' feedback, Montessori classrooms encourage students to work independently with materials specially designed to support learners discovering errors for themselves. We found that Montessori students paused longer post-error in early childhood and, by adolescence, were more likely to self-correct. We also found that a developmental shift from longer to shorter pauses post-error being associated with self-correction happened younger in the Montessori group. Our findings

provide preliminary evidence that educational experience influences performance monitoring, with implications for neural development, learning and pedagogy.

To be successful in school, children must learn to distinguish correct from incorrect responses. To do this, they must monitor their own performance, noticing when their work is flawed and efficiently adapting their behavior. That is, they must notice, learn from and correct errors.

Performance monitoring comprises the set of behavioral and neuronal responses that individuals show in reaction to unexpected outcomes. When individuals notice something unexpected, such as an error, they tend to pause, a phenomenon known as Post-Error Slowing (PES; Ullsperger, Danielmeier, & Jocham, 2014). To learn from the discrepant event, they must adapt their behavior accordingly (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004), a phenomenon measured as post-error improvement in accuracy (PIA; Danielmeier & Ullsperger, 2011; Schroder & Moser, 2014).

The response to own error is measured through conflict tasks (e.g. Flanker task, Simon task, Go/noGo task), where congruent and incongruent conditions require task-specific response monitoring. PES can be computed as the reaction time (RT) difference between post-error and post-correct responses. While a multitude of infant looking time and electrophysiological studies show that by 2-3 months children detect and respond to deviant events (Dehaene-Lambertz, 2000; Dehaene-Lambertz & Gliga, 2004), PES has not been measured in children until about age 3 y. (the Simple Simon Task; Jones, Rothbart, & Posner, 2003). However, developmental data are inconsistent, sometimes showing invariant (Davies, Segalowitz, & Gavin, 2004; Ladouceur, Dahl, & Carter, 2007; Santesso, Segalowitz, & Schmidt, 2006), and sometimes increasing (Santesso & Segalowitz, 2008) or decreasing (Carrasco et al., 2013; Hajcak, Franklin, Foa, & Simons, 2008; Smulders, Soetens, & van der Molen, 2016) PES across age. Neural developmental studies have also reported inconsistent outcomes in error-related brain components and their trajectories (Tamnes, Walhovd, Torstveit, Sells, & Fjell, 2013). These contradictory results may reflect task design features such as inter-stimulus timing or difficulty-level (Dutilh et al., 2012), but they have also been proposed to reflect the instability of children's error monitoring (Smulders et al., 2016). Taken together with a behavioral study reporting that PIA increases with age (Overbye et al., 2018), such data suggest the possibility that the relationship between PES and PIA changes with development (Brewer & Smith, 1989). Perhaps longer post-error pauses are adaptive in early childhood, when children require time to effortfully stop and redirect, while shorter pauses post-error may be the hallmark of efficient and automatic self-correction by adolescence. This would be in line with the literature reporting a shift in how children process learning signal saliency (van Duijvenvoorde, Zanolie, Rombouts, Raijmakers, & Crone, 2008; van den Bos, Guroglu, van den Bulk, Rombouts, & Crone, 2009).

In addition to the possibility of a developmental shift in adaptive use of post-error pauses, these apparently contradictory results could reflect variability of experience, particularly in school. Such environmental influences would be consistent with known experience-dependent effects on the development of executive functioning (Davidson, Amso, Anderson, & Diamond, 2006), for example in children experiencing different school curricula (Diamond, 2012). If true for executive functions, related competencies could be impacted as well. Here, we hypothesize that even among children from relatively privileged backgrounds, school pedagogical approach may modulate the processes by which children come to notice and respond to their own errors.

Pedagogical traditions differ on how they teach children to learn from feedback, though school-based influences on the development of performance monitoring have not been investigated to our knowledge. For example, traditional education provides children from one age group with opportunities to engage in work, and then to learn about and correct their performance later based on a teacher's feedback. By contrast, Montessori education focuses on supporting children in self-correcting in real time. It utilizes specialized materials that encourage children's self-discovery of relevant concepts, and multi-age classes in which children discuss correct and incorrect answers as they work.

Given these open developmental and experience-related questions, the purposes of this study are: (1) to examine PES and PIA development across childhood and early-middle adolescence; and (2) to evaluate whether children from equivalently high-quality pedagogical environments with systematically different pedagogical approaches differ in their developmental trajectories of performance monitoring. Accordingly, we measured post-error slowing and post-error improvement in accuracy among groups of Montessori and traditionally-schooled children during the completion of a child-friendly Flanker Task (Eriksen & Eriksen, 1974). We hypothesized that: (a) PES would decrease with age; (b) PIA would increase with age; (c) there would be a developmental shift in the relationship between PES and PIA such that young children's longer pauses, and adolescents' shorter pauses, would be associated with more effective self-correction; (d) these developmental effects would be stronger in the Montessori group; (e) by adolescence, Montessori students would show lower PES and higher PIA than their traditionally schooled peers.

The study was conducted in Switzerland, where alternative education is only found within private schools. As a consequence, the Montessori schools in this study were private.

Accordingly, we had no option for a lottery design study. Given these constraints, we selected Montessori and traditional schools from the same neighborhoods and of similarly high academic quality, and confirmed that participating groups of students did not differ on the basis of family SES, fluid intelligence or age.

Methods

The study was conducted in accordance with the Declaration of Helsinki and the research protocol was approved by the University ethics committee. The study is part of a larger project investigating effects school pedagogy on children's brain development. Teachers' and pupils' participation was voluntary.

Recruitment site selection: Schools were selected to include children from affluent areas only, using official government data on mean salary. Traditional and Montessori schools co-existed in the same neighborhoods and were of similar academic quality as judged by adherence to either official Montessori qualifications or government specifications for public schools.

Traditional schools were public and were identified based on their adherence to the official local study plan. This plan strictly implies, as from 7 years old, that children are provided:

(i) lecture-style, interactive teaching;
(ii) feedback in the form of grades and summative assessments;
(iii) breaks every hour;
(iv) age-specific class groupings (i.e. one grade level per class).

Prior to 7 years old, traditionally-schooled children are provided play-oriented curricula with emphasis on building gross and fine motor skills and social skills.

Montessori schools were private and were selected following the criteria set by the International Montessori Association (https://montessori-ami.org) to ensure high fidelity implementation of the curriculum (Lillard, 2012), such that:

(i) all teachers were Montessori-trained and there was a complete set of Montessori materials in each classroom;

(ii) children were not provided formal grades or summative assessments on work;

(iii) children had 3 hours of continuous work time each day;

(iv) classes contained at least 3 different grade levels;

Prior to 7 years-old, Montessori curricula emphasize independent learning from specialized materials designed to refine the senses and teach early academic skills.

Participants: 10 traditional and 13 Montessori schools were selected to participate. Consent letters were sent home to all parents of children ages 4 to 15, and 234 children's parents consented. An additional 4 children were consented but excluded due to having made no errors (accuracy rate of 100%; n=2), or being outside the target age range (older than 15.5 y.; n=2). The final sample consisted of 234 children from 4.4 to 15.3 y. (M_{age} = 9.02 years old, SD = 2.43 y., 114 girls and 120 boys); 111 participants were enrolled in the traditional educational system (59 girls), and 123 were schooled in the Montessori educational system (55 girls).

Study protocol: The experiment took place in the children's schools. Participants were seated in a separate room outside their classroom. Assessments of both groups were conducted by four trained experimenters (including the first author).

Group comparison. To ensure between-group homogeneity, we tested for pedagogical group differences in: (i) age; (ii) gender; (iii) socio-economic status [SES; measured through a parental questionnaire (Genoud, 2011) that 78.6% filled out, 84.7% in the traditionally-schooled group and 73.2% in the Montessori group]; and (iv) fluid intelligence (FI), evaluated using the black-and-white version of the Raven's Progressive Matrices task (Raven, Raven, & Court, 1998).

PES and *PIA* were assessed using RT and accuracy from a child-friendly version of the Flanker task (Eriksen & Eriksen, 1974), presented via Presentation® software. The child was asked to "feed hungry fish" by pressing the key facing the same direction as the target fish in the display (five fishes in line). Each child completed three blocks, the first two of which were preceded by training sessions. In the first block, the child was instructed to focus on the fish at the center of the line (17 trials). In this block, all stimuli (fishes) were blue. In the second block, the child was instructed to focus on the fishes flanking the central one (17 trials). In this block, all stimuli were pink. In the final block, the child was instructed to focus either on the inside fish or on the outside, flanker fish, depending on their color (45 trials). Due to RT change across age, the response time limit was 2000 ms up to 6 years old, and 1500 ms for older children.

Dependent variables. We examined PES and PIA measures across age and tested for interactions by pedagogical group.

Statistical analyses were done with the Jamovi open-source software (Version 0.9; The jamovi project (2019). Retrieved from https://www.jamovi.org).

Results

Pedagogical group demographic comparison. Independent samples *t* tests showed no pedagogical group differences in age, SES background or fluid intelligence (FI) scores (all $p > .4$; see Table 1). A χ^2 test showed no group differences in gender distribution.

Pedagogical group task performance comparison. One-way ANCOVAs showed no statistically significant differences between Montessori and traditional students on either mean Reaction time (RT) or Error rate, controlling for age (RT: $F(1,230) = 0.34$, $p = .56$, $\eta^2 = 0.001$; Error Rate: $F(1,230) = 1.29$, $p = .26$, $\eta_p^2 = 0.006$). As expected, RT and Error rate significantly decreased with age (RT: $F(1,230) = 295.52$, $p < .001$, $\eta_p^2 = 0.56$; Error Rate: $F(1,230) = 167.10$, $p < .001$, $\eta_p^2 = 0.42$).

PES. The detection of errors was investigated by comparing the RT after correct and incorrect responses. Following previous studies' protocol (Eriksen & Eriksen, 1974; McDermott, Perez-Edgar, & Fox, 2007), we computed differences in valid RT[1] (RT > 250 ms and within 2 SD) between post-error and post-correct trials ($RT_{post\text{-}error} - RT_{post\text{-}correct}$). We computed a one-way ANCOVA with age as the covariate and pedagogy as a fixed factor, and the interaction term (pedagogy*age). The analysis revealed that PES increased with age, $F(1,230) = 4.99$, $p = .026$, $\eta_p^2 = 0.02$. There was no effect of pedagogy on PES, $F(1,230) = 2.26$, $p = .134$, $\eta_p^2 = 0.01$, and no significant interaction between pedagogy and age on PES, $F(1,230) = 1.76$, $p = .186$, $\eta_p^2 = 0.001$. To accommodate the possibility that the developmental change would not be linear, we ran an additional age-group analysis. We divided the children into four age groups with cut points corresponding as closely as possible to school transitions, i.e. from Kindergarten to grade school; from early to middle grade school; from middle grade school to pre-adolescent classrooms; from early adolescence onward. Groups spanned an average of 2.5

[1] *Analysis with raw RTs strengthens the findings. However, to avoid that outlier trials drive the significant results, RTs outside 2 SD were filtered out.*

years (see Table 2). To test differences in developmental pattern in PES, we computed a two-way ANOVA with age-group, pedagogy and the interaction term (age-group*pedagogy) as fixed factors and confirmed an age-group difference, $F(1,226)=2.67$, $p=.048$, $\eta_p^2=0.034$. A post-hoc t-test revealed that pedagogical groups differed in PES from age 4.5 to 9 y.; traditional students showed significantly less PES in this age range ($t(226)=-3.16$, $p_{tukey}=0.038$; see Figure 1A).

PIA. Self-correction post-error was computed as the ratio of error trials that were immediately followed by a correct trial, divided by the total number of error trials. The ANCOVA analysis revealed that PIA increased with age, $F(1,230)=104.76$, $p<.001$, $\eta_p^2=0.31$. Pedagogy was associated with PIA at the trend-level, $F(1,230)=3.09$, $p=.08$, $\eta_p^2=0.013$, with overall self-correction post-error slightly higher in Montessori students. As hypothesized, there was a significant interaction between pedagogy and age on PIA, $F(1,230)=4.08$, $p=.045$, $\eta_p^2=0.02$, such that Montessori students showed a stronger developmental increase in self-correction. A two-way ANOVA on PIA by age-group, pedagogy and the interaction term (age-group*pedagogy) further confirmed a significant increase across age-groups, $F(1,226)=32.39$, $p<.001$, $\eta_p^2=0.30$, an effect that was stronger in the Montessori older schoolers ($p_{tukey}<0.025$; see Figure 1B).

The relationship between PES, PIA and Pedagogy shifted with development. In a linear regression model, PES, age, pedagogy and the interaction terms (age*PES, age*pedagogy, pedagogy*PES), age, PES, and age*PES were all predictors of PIA ($R^2=0.34$; all $p<0.035$), such that as students grew older, the less PES they showed, the greater PIA they showed. Pedagogy was nearly a significant predictor of PIA in this model ($p=0.052$). Furthermore, there was a significant interaction between pedagogy and age such that Montessori students showed a stronger and earlier developmental effect ($F(1,227)=5.72$, $p=0.018$; see Figure 2).

By adolescence (age 11-15y.), Montessori students showed lower PES and greater PIA than their traditionally schooled peers (PES: $t(46)=2.13$, $p=.039$; PIA: $t(46)=2.14$, $p=.037$).

Discussion

In this study we compared PES and PIA in traditional and Montessori schoolers across age, with the aim of mapping developmental differences in performance monitoring in the flanker task, and observing how developmental changes in performance monitoring may be influenced by pedagogy. The age range included in our study, from 4 to 15 years old, corresponds to the broad developmental period in which the brain regions responsible for conflict monitoring and error recognition and correction are maturing (Kelly et al., 2009; Velanova, Wheeler, & Luna, 2008). It is also the age range in which schooling is known to have a profound effect on cognitive skills (e.g. on IQ; Falch & Massih, 2011).

We found that, whether attending Montessori or traditional school, as children grew older both their PES and their PIA increased, partially corroborating previous studies (Overbye et al., 2018; Smulders et al., 2016). Interestingly, the developmental increase in PES we observed was largely driven by the younger children (<9 years old) enrolled in traditional schools. In our study, the youngest Montessori students' PES was similar to that of the oldest students, suggesting an earlier maturation of the capacity to detect response errors. These findings may possibly explain inconsistencies between previously reported findings (Smulders et al., 2016); our data suggest that the ability to detect response errors is especially malleable up to 9 years old, and may be trained by schooling. Of note, the number of errors did not differ between pedagogical groups at any age; instead, it was the capacity for self-correction that showed pedagogical effects.

The relationship between PES and PIA also changed with age: in young children, pausing after an error was associated with a subsequent self-correction. This was no longer the case among adolescents, for whom shorter pauses were associated with more effective self-correction. The developmental shift from longer to shorter pauses being associated with more effective self-correction happened at a younger age among Montessori students (approximately at age 8 versus at age 10). Together these results shed light on the developmental trajectory of performance monitoring across childhood and early-mid adolescence, and suggest that error recognition may be modulated by early school experience (< 9 years old), with implications for self-correction in adolescence. Future longitudinal work is needed to uncover the developmental processes that undergird our findings, and to better understand the implications of these findings for children's development and learning more broadly.

Over the course of schooling, children learn to associate salient events like task outcomes with context-dependent feedback, and to adjust behavior. Our results could possibly reflect the Montessori curriculum's relative emphasis on students building early awareness of the sensory properties of materials (i.e. learning to discriminate forms, colors, textures, temperatures, etc.), without waiting for a teacher's feedback or external reinforcers (e.g. grades, rewards, etc.; Dolan & Dayan, 2013; Glascher, Daw, Dayan, & O'Doherty, 2010). This may serve to orient Montessori students toward directly perceiving information about outcomes in academic tasks and may teach them to more effectively self-monitor in academic tasks. Whereas the free play orientation used early in traditional schools may benefit children in other ways (Lillard, 2017), it may not orient children to notice errors on academic-style tasks as effectively.

The social-affective orientation toward errors in Montessori and traditional classrooms my further contribute to our effects. Montessori students' reliance on direct sensory perceptions as feedback may be reinforced by the culture of the Montessori classroom, which emphasizes non-competitive peer-to-peer teaching within classes of students of different ages. Previous research has demonstrated that cooperative environments lead to more effective shared learning from errors, and hence to better transfer of knowledge (Koban, Pourtois, Vocat, & Vuilleumier, 2010). By contrast, the delayed, teacher-provided evaluative feedback in traditional classrooms may lead students to become increasingly reactive to errors, which come to be negatively valenced, privately conveyed from the teacher to the student, and socially stigmatized. As formal instruction is instituted and the grading system for external valuation of work takes hold, traditionally-schooled children learn to value correct answers provided by their teachers and to avoid, rather than productively engage with, errors (Hayek, Toma, Guidotti, Oberlé, & Butera, 2017; Hayek, Toma, Oberle, & Butera, 2014, 2015). Indeed, a study suggests that correct answers are selectively associated with positive valence in traditionally-schooled children, while Montessori students show no such effect (Denervaud et al., *in review*).

Our interpretation builds from the basic distinction between internally-derived, sensory learning and externally-derived, value-based learning that is fundamental to learning theories, including for example to work on extrinsic versus intrinsic motivation (Oudeyer, Gottlieb, & Lopes, 2016; Ryan & Deci, 2000) and reinforcement learning (Dolan & Dayan, 2013; Frank, Woroch, & Curran, 2005; Glascher et al., 2010; Worthy, Cooper, Byrne, Gorlick, & Maddox, 2014). If we are correct, it would suggest that many types of experiences that support children in building skills for safe and adaptive self-directed learning should support children's performance monitoring development. It is possible that, for example, the strong outcomes found with well-designed and supported project-based learning (Condliffe et al., 2017; Knecht, Gannon, & Yaffe, 2016) could have a similar effect, or, for that matter, increased proportions of productive self-directed time during childhood (Barker et al., 2014). This study has two main limitations. First, the study is cross-sectional. Though the study includes a continuous age range of students, longitudinal work with children experiencing different styles of pedagogy would increase confidence in the developmental trajectories described here. Second, the study has a non-randomized design. It is possible that parents who value self-directed behavior themselves are more likely not only to enroll their children into Montessori schools but also to encourage their child to err and autonomously correct themselves on academic tasks at home. That said, we find it unlikely that the effects we report here are entirely due to selection biases. A study of scholastic, social-emotional and creativity measures in students from the schools included here produced similar effect sizes as have existing randomized studies in other Montessori and traditional schools (Lillard & Else-Quest, 2006; Lillard et al., 2017; Denervaud, Knebel, Hagmann, & Gentaz, 2019).

In conclusion, our findings suggest that children from 4 to 15 years of age develop performance monitoring, and that this development may be influenced by the pedagogical approach they experience at school. Our findings provide preliminary evidence that inconsistencies in previous studies may be due in part to classroom experience. Our results also suggest the possibility that early and strong development of the capacity to discriminate errors, though this requires time in young children, may have downstream developmental effects on the ability to efficiently self-correct in adolescence.

Debates in education often focus on the most appropriate ways to optimally provide content-area knowledge to students. Our findings reiterate the importance of understanding how pedagogical orientations toward the learning process, and not simply curricular content itself, are important factors shaping children’s development. The findings also point to the need for nuanced developmental studies of children’s cognitive, affective and social capacities and their interactions in various school contexts (Immordino-Yang, Darling-Hammond, & Krone, 2019). Given the rapid pace of societal change youth face, it is of utmost importance that educational experiences equip children not simply with knowledge but with abilities to effectively and flexibly learn independently. Our study provides a small step toward connecting research on performance monitoring with the development of mental processes in children's educational environments.

Data availability

The data that support the findings of this study are available from the corresponding author upon motivated request.

Competing interests

The authors declare no competing interests.

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	Group		
Control variables	Montessori (n=123)	Traditional (n=111)	χ^2 or t-test
Age, mean (SD)	8.89 (2.34)	9.17 (2.53)	*t*(232)=-0.87, *p*=.39, ns
Age min, max	4.40, 15.2	4.50, 15.3	ns
Gender (N girls)	52	59	χ^2(1,231)=2.23, *p*=.14,ns
Socio-Economic Status (SD)	0.70 (0.11)	0.70 (0.12)	*t*(182)=-0.006, *p*=.99, ns
Fluid Intelligence, mean (SD)	30.1 (7.81)	29.6 (6.61)	*t*(209)=0.56, *p*=.58, ns
Mean RT (SD)	878.28 (199.52)	878.09 (191.28)	*t*(232)=0.007, *p*=.99, ns
Error rate (SD)	20.95 (14.72)	20.94 (12.79)	*t*(232)=0.08, *p*=.99, ns

Table 1: Participant demographics and control variables.

Pedagogy	Age-group	Mean Age	SE
Montessori	4.5-6 y.	5.35	0.159
	6-9 y.	7.75	0.125
	9-11.5 y.	10.19	0.107
	11.5-15 y.	12.36	0.187
Traditional	4.5-6 y.	5.31	0.167
	6-9 y.	7.29	0.167
	9-11.5 y.	10.04	0.106
	11.5-15 y.	12.56	0.163

Table 2: Groups per pedagogy. To complement our continuous analysis, we additionally ran an age-group discrete analysis. Accordingly, children were divided into four groups. A two-way ANOVA confirmed that mean ages did not differ by pedagogical group (*F*(3,226)=1.49 , *p*=.217). SE stands for standard error.

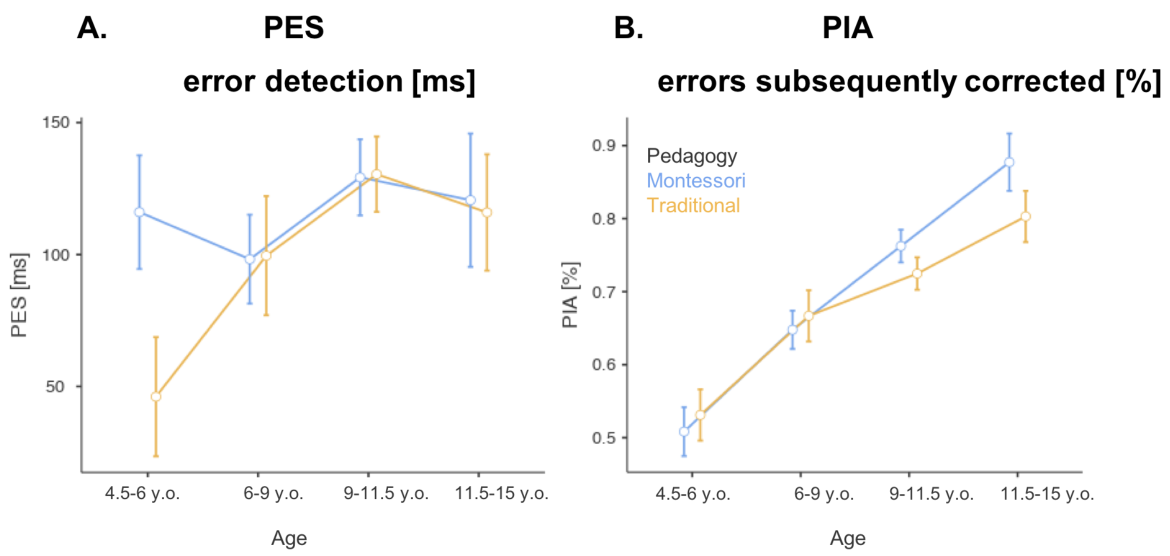

Figure 1A Post-Error Slowing (PES) as a measure of error-detection. ΔRT (M_{RT} of trials$_{incorrect}$ - trials$_{correct}$[ms] over all valid trials) as a function of age-group showing that young children differ in their PES pattern according to their pedagogical experience, while older students do not. **1B Post-Error Improvement in Accuracy (PIA) as the percentage of errors that were subsequently corrected.** Post-error correct trials over the total number of errors as a function of age-group boxplots showing that 9-15 year-old students differ in PIA pattern according to their pedagogical experience, while younger students do not. For both graphs, error-bars display standard-error (SE).

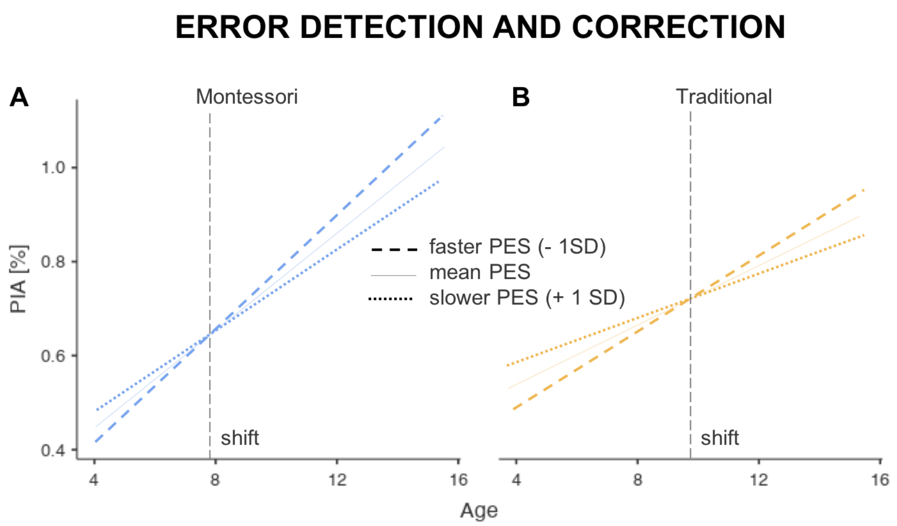

Figure 2: Pedagogical influence on the relationship between error detection (PES) and error correction (PIA). PIA was reliably predicted by age and age*PES, such that younger children who slowed more after errors (slower PES; mean RT+1SD) were more likely to self-correct, while older children who slowed less after errors (faster PES; mean RT-1SD) were more likely to self-correct. Pedagogy effected this developmental shift, which happened earlier in Montessori than in traditionally schooled students.