Children's automatic evaluation of self-generated actions is different from adults

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Research highlights

- Response errors led to post-error slowing in both children and adults.
- Response errors were associated with negative affect in adults only.
- In children, correct responses were related to positive affect.
- Montessori pedagogy influenced the affective processing of actions.

Abstract

Performance monitoring (PM) is central to learning and decision-making. It allows individuals to swiftly detect deviations between actions and intentions, such as response errors, and adapt behavior accordingly. Previous research showed that in adult participants, error monitoring is associated with two distinct and robust behavioral effects. First, a systematic slowing down of reaction time speed is typically observed following error commission, which is known as post-error slowing (PES). Second, response errors have been reported to be automatically evaluated as negative events in adults. However, it remains unclear whether (i) children process response errors as adult do (PES), (ii) they also evaluate them as negative events, and (iii) their responses vary according to the pedagogy experienced. To address these questions, we adapted a simple decision-making task previously validated in adults to measure PES as well as the affective processing of response errors. We recruited 8 - 12 year old children enrolled in traditional (N = 56) or Montessori (N = 45) schools, and compared them to adults (N = 46) on the exact same task. Results showed that children processed correct actions as positive events, and that adults processed errors as negative events. By contrast, PES was similarly observed in all groups. Moreover, the former effect was observed in traditional schoolchildren, but not in Montessori schoolchildren. These findings suggest that unlike PES, which likely reflects an age-invariant attention orienting towards response errors, their affective processing depends on both age and pedagogy.

Keywords: performance monitoring - development – response error – evaluative priming – post-error slowing – pedagogy – Montessori pedagogy

Central to learning and decision-making stands the remarkable ability to rapidly evaluate the outcome of our actions as good or bad, and to adapt our behavior accordingly. In adults, response errors provide a unique window into performance monitoring (PM), which is closely related to self-regulation (Inzlicht, Bartholow, & Hirsh, 2015) as well as value-based decision-making (Ullsperger, Danielmeier, & Jocham, 2014). Given the limited research on PM in children, the main goal of our study was to shed some light on this process.

Post-Error Slowing

In adults, the cognitive architecture underlying PM has been conceived as a feedback loop that monitors possible deviations between action and goal, and assigns value to actions. Based on this evaluation, remedial processes can subsequently take place (Ullsperger, Danielmeier, & Jocham, 2014; Ullsperger, Fischer, Nigbur, & Endrass, 2014). At the behavioral level, they can be explored using Post-Error Slowing (PES; Rabbitt, 1966). PES translates the systematic slowing-down in reaction time (RT) speed for trials following response errors versus correct responses. Although PES has long been conceived as adaptive (i.e., increasing the likelihood of post-error accuracy and/or reflecting enhanced cognitive control; see also Botvinick, Braver, Barch, Carter, & Cohen, 2001), recent models and data (see Ullsperger & Danielmeier, 2016, for a review) have challenged this view suggesting that it could also probably reflect unspecific attention processes to some degree, including an automatic orienting response to deviant events (Notebaert et al., 2009). Since errors are usually oddball in the trial series, they unlock PES. According to this view (see also Wessel, 2018), PES reflects a blend of both adaptive and unspecific adjustment effects following error commission.

In children, research on PES is scant. Accordingly, it remains unclear whether they also automatically orient their attention towards response errors. Earlier work already showed that PES could be found in children as young as 3 years old (Jones, Rothbart, & Posner, 2003), suggesting an early onset in life, which is in line with the view that it is likely subtended by an exogenous attention control system that can operate and mature rapidly after birth (Colombo, 2001). Given this evidence, it is likely that older children (e.g. 8-12 years old), very much like adults, could exhibit PES (see also Smulders, Soetens, & van der Molen, 2016). The first goal of our study was to address this question.

Errors are negative

Besides the behavioral adaptation following errors (i.e., PES), these worse-than-expected events are also associated with distinct affective processing. More specifically, accumulating evidence shows that response errors are perceived by adults as negative events compared to correct responses (Pourtois et al., 2010; Koban & Pourtois, 2014; see also Dignath, Eder, Steinhauser, & Kiesel, 2019); this evaluation is rapid and automatic (Aarts, De Houwer, & Pourtois, 2012). Using a priming methodology, it has been shown that after response errors, young adults categorize negative words faster and better than positive words, suggesting a link between these events and negative valence (see also Aarts, De Houwer, & Pourtois, 2013 and De Saedeleer & Pourtois, 2016 for replications). Interestingly, the reverse effect (i.e., assigning a positive value to correct responses) was much weaker in these earlier studies, suggesting an asymmetry in the affective processing of self-generated actions in adult participants. Furthermore, this evaluative effect did not correlate with PES, suggesting that the processing of response errors as aversive is unrelated to the automatic orienting towards deviant events in young adults. Presumably, by analogy with PES, the affective processing of response errors as negative events could also be deemed adaptive since it might serve to quickly identify them, and in turn foster error-based learning, with the goal of protecting the organism from possible bad or deleterious consequences.

However, whether or not young children automatically assign a negative value to their response errors, like adults do (Aarts et al., 2012), remains an open question. Previous research showed that toddlers express complex emotions such as shame or anger when failing to reach a goal, suggesting that they can assign negative value to breakdowns in self-efficacy. More generally, they usually show a negative bias whereby "bad" is stronger than "good" when it comes to stimulus or outcome evaluation (Vaish, Grossmann, & Woodward, 2008). Accordingly, one could conjecture that response errors are probably already processed as negative events in toddlers. However, toddlers' behavior is usually characterized by active exploration and guided by trial and error, which indirectly suggests, contrary to what has been found in young adult participants (Aarts et al., 2012), that they do not necessarily assign a negative value to response errors. For children, response errors, conflicts, or challenges usually correspond to valuable learning opportunities that allow them to acquire and transform knowledge (Gopnik & Wellman, 2012). These distinctive events allow them to adjust and update the mental representations that form as well as structure newly acquired information (Fischer & Rose, 1996; Montessori, 1936; Piaget, 1952; Vygotsky, 1978). Interestingly, the minimization of error probability is thought to underlie and drive cognitive development (Oudeyer & Smith, 2016). Moreover, children actually preferentially allocate attention towards surprising events, such as novel stimuli, and exhibit an intrinsic motivation, or curiosity, to learn from them (Gopnik & Bonawitz, 2015).

Children undoubtedly can detect and react to events that violate or challenge their expectations, however, it remains unclear whether they automatically evaluate response errors as negative events. The second goal of our study was to assess the automatic affective processing of response errors in children, and to compare it to adults.

Influence of Pedagogy

During childhood, exploration and learning are strongly influenced by the environment in which they take place. Therefore, the specific pedagogy experienced by children in school is an important determinant of how exploration and learning develop as well as manifest (Kaplan & Patrick, 2016; Kang et al., 2009; Oudeyer, Gottlieb, & Lopes, 2016). Additionally, it might also influence their "natural" processing of response errors as negative, or even as positive events. In many Western countries, a traditional pedagogy is often used (PISA; Grisay, de Jong, Gebhardt, Berezner, & Halleux-Monseur, 2007). This pedagogy evaluates learning progresses through formal assessments, typically with the use of grades or other forms of evaluative feedback, such as rewards or punishments. The child's knowledge is typically assessed by means of a test or an exam, and incorrect responses are penalized and can eventually lead to a low grade. In contrast, the Montessori pedagogy, which is less frequently used and encountered in these countries, offers an alternative approach, where learning and development are promoted without the use of incentives and reinforcers (Lillard & Else-Quest, 2006; Marshall, 2017; Montessori, 1936; Rathunde, 2001). More specifically, through independent or peer-to-peer exploration in the absence of evaluative feedback from the teacher, learning is facilitated and self-efficacy is eventually stimulated (Denervaud, Knebel, Hagmann, & Gentaz, 2019; Denervaud et al., 2020; Denervaud, Knebel, Immordino-Yang, & Hagmann, 2020; Lillard et al., 2017). In this context, incorrect responses are not penalized but they actually correspond to learning opportunities. Accordingly, it is conceivable that the specific pedagogy experienced by children may exert a modulatory effect on the way they process response errors as distinctive affective events and orient their attention to them (as expressed by PES). Presumably, the Montessori pedagogy might have a different impact on the affective processing of response errors than the traditional one, even though in both cases, PES could be found. The last goal of our study was to put this hypothesis to the test.

To this end, in this study, we adapted the experimental procedure previously devised and validated by Aarts et al. (2012) and De Saedeleer & Pourtois (2016) on young adults. More specifically, we asked 8-12 year old children (experiencing either the traditional or Montessori pedagogy) and young adults to perform the same simple speeded Go/noGo task. Given the strict response time limit imposed, participants sometimes committed response errors. Importantly, after each trial of the Go/noGo task, participants had to categorize as quickly as possible whether an emotional word shown on the screen was positive or negative (second task). Following the logic of evaluative priming (Jones, Olson, & Fazio, 2010), this second task probed the affective processing of response errors (first task) by the participants. More specifically, we assessed if emotional word categorization was globally delayed following response errors compared to correct responses (suggesting PES), as well as whether negative words were selectively processed faster than positive words following response errors (suggesting evaluative processing of response errors as negative events). Taking into consideration the literature reviewed above, we hypothesized that PES should be observed in young adults as well as children. Moreover, we postulated that in young adults, response errors would be processed as negative events, thereby replicating the findings of Aarts et al., (2012). In children, we explored if a similar evaluative processing of errors could be found (Vaish et al., 2008), and whether it could be influenced by the pedagogy experienced by the children at school, focusing on a direct comparison between Montessori and traditional pedagogy.

Method

Ethics

The experiment was conducted in accordance with the Declaration of Helsinki. Written parental consent and verbal assent for participation was obtained for each child, and informed consent was provided by each adult participant.

Participants

One hundred-and-ten schoolchildren participated in the experiment. The selection criteria were age (8 to 13 years old) and pedagogy. Children with missing data (*n* = 2, Montessori schoolchildren) or outside the target age (*n* = 7) were excluded from the study (*n* = 9), resulting in 101 children participants (M_{age} = 10.4, *SD* =1.1), 45 enrolled in the Montessori schooling system (M_{age} =10.3, *SD* =1.2, 17 girls) and 56 in the traditional one (M_{age} =10.5, *SD* =1.1, 29 girls). In addition, 55 adult participants took part in the study either for course credit (28 undergraduate psychology students) or for 15 CHF (27 recruited outside the University). Adults who did not commit errors in all conditions and had therefore missing data were removed (*n* = 9), resulting in 46 adult participants (M_{age} = 28.0, *SD* =9.4, 30 women).

Demographic and socio-economic variables

For children, we collected information on their age, gender, fluid intelligence (Raven, Raven, & Court, 2003) and socio-economic background (SES; Genoud, 2002) to assess whether the two groups were comparable on these variables. For the adults, we only collected information on their age and gender.

Evaluative Priming Task

Participants performed an adapted version of the speeded Go/noGo task (Vocat, Pourtois, & Vuilleumier, 2008); following each Go/noGo trial, they categorized an affective word (see Figure 1; see Aarts et al., 2012). Given that we mainly focused on the affective processing of response errors, those errors committed during the first task (Go/noGo) served as primes for the word categorization task.

Go/noGo task. We adapted the stimuli of the Go/noGo task to make it child-friendly. Instead of arrows, we used rich and colorful stimuli (i.e., diamonds) that the participants were asked to chase in a game-like environment. The diamonds (diameter of ~7.14 cm) had different colors: green (average relative luminance of 32.8%), red (average relative luminance of 23.0%), or pink (average relative luminance of 35.1%). These stimuli were retrieved from an online open-source data base (www.pexels.com). During each trial, the first diamond to appear on screen was always green. It was followed by a second diamond that would either be similar (green) or change in color (red or pink; see Figure 1). The former corresponded to the imperative stimulus (i.e., Go trial), while the latter required response inhibition (i.e., noGo trials).

Evaluative Categorization Task. The stimuli were 15 positive and 15 negative words selected from the Affective norms for French words rated by a group of children and adolescents, and a group of adults (Monnier & Syssau, 2017). These words were either nouns or adjectives (see Table S1). Using the database's information on valence and arousal ratings (Monnier & Syssau, 2017), we ensured the selected words' valence ratings did not significantly differ between children and adults ($F(1,56) = 0.016$, $p = .90$).

Procedure

The task was performed on a computer. The stimuli were presented in the center of the screen, on a white background. Given the limited and fluctuating attention capacity of children, we shortened the experiment from the 540 test trials used by Aarts et al. (2012) to 100 test trials. The experiment was composed of a training block (24 trials, corresponding to 16 Go and 8 noGo trials), followed by 4 test blocks of 25 trials each, totaling 100 trials (68 Go and 32 noGo, randomly presented). Each trial started with a fixation cross (500 ms), followed by a green diamond shown for a duration varying randomly between 1000 and 2000 ms. This jitter was introduced to reduce possible anticipatory effects for the second diamond. After its presentation, a blank screen (250 ms) was presented before the second diamond appeared. Its duration was determined based on reaction times recorded during the first test block, ensuring subject-specific calibration. Similar to Aarts et al. (2012), we used a conservative cutoff and adjusted the stimulus duration of the second diamond in the three subsequent test blocks to be 70% of the mean RT on Go trials (first test block).

Akin to Aarts et al. (2012), RTs on go trials were labelled online as either fast or slow hits. Fast hits corresponded to RTs falling below this arbitrary RT cutoff, and were associated with a positive performance feedback. In comparison, slow hits were RTs above it and were associated with a negative performance feedback (i.e., “too slow”, “correct”). This procedure was used to promote making speedy decisions and used to increase the likelihood of committing errors on the noGo trials. After the Go/noGo decision, a blank screen was presented for 300 ms, followed by the presentation of an emotional word (with either a positive or negative valence, see Figure 1) until a response was registered. Participants were asked to perform a two alternative forced choice (2AFC) task based on the valence of the word. Across trials and participants, the presentation was randomized, such that both the Go and noGo trials were followed by a similar amount of positive and negative words. Moreover, this procedure ensured that on average, the 30 words were sampled a similar number of times. At the end of each trial, general performance feedback was presented for 1000 ms to inform participants about the accuracy and speed of their Go/noGo decisions, as well as their accuracy in the emotion word categorization task.

Participants were asked to use their non-dominant hand for the Go/noGo task and their dominant hand for the 2AFC categorization task. This way, we could rule out that the evaluative priming was simply explained by the motor effector shared between the two tasks.

Data Analyses

First, we compared the two groups of children on the demographic and socio-economic variables. Next, we compared the three groups of participants on the Go/noGo task. Last, to test our specific hypotheses, we compared them on the affective word categorization task.

Demographic and socio-economic variables

For each variable, a *t*-test (Student's or Welch's according to the preliminary data check with Q-Q plots and Levene's test) with a 95% confidence interval (CI) for the mean difference was conducted, with a false-rate discovery (FDR) p value correction set at q =.05. A chi-squared test was performed to assess whether gender distribution was similar between groups or not. None of them were significant ($p > .05$), revealing that the two groups of children did not significantly differ from another in regards to age, gender, socio-economic status, or fluid intelligence (Table 1).

Go/noGo Task

Accuracy. We extracted False Alarms (FAs), Hits, Correct Rejections and Misses for each group (adults, traditional, and Montessori schoolchildren) separately (see Table S2). Subsequently, a mixed-model analysis of variance (ANOVA) was performed to assess possible group differences in accuracy. We also assessed whether the ratio of fast vs. slow hits significantly differed between groups.

Reaction time. We computed the mean reaction time (RT) for Hits and compared the three groups on this measure using an ANOVA.

Affective Word Categorization Task

Reaction time. Given the large RT differences between adults and children precluding a direct comparison to be drawn between them, RTs for correct responses were first z-transformed using the following formula $(RT\text{-}RT_{group\ mean})/SD_{group}$. To test our a priori hypotheses, we first performed a mixed-model ANOVA on these z-scored RTs with VALENCE (positive vs. negative) and ACTION (Hits vs. FAs) as within-subject factors, and GROUP (adults, traditional or Montessori schoolchildren) as a between-subjects factor. Fast and slow Hits were combined for this analysis as the experimental procedure was kept short to remain child-friendly, and the Go/noGo task generated a limited number of Hits in total. As the three-way interaction was significant (see Results), we then performed three ANOVAs on the non-transformed RTs, for each group separately (adult, traditional and Montessori schoolchildren), with ACTION and VALENCE as within-subject factors (with $\alpha < .05$). Post-hoc Tukey tests were computed when appropriate.

Accuracy. We analyzed the percentage of correct responses applying the same statistical model used for the RTs.

Results

Go/noGo Task

Accuracy. Across the three groups, participants' mean accuracy was significantly higher in the Go (M = 75.4%, SE = 23.8%) than in the noGo trials (M = 33.5%, SE = 23.8%), $F(1, 144) = 201.8$, $p < .001$, $\eta^2_p = 0.58$. Furthermore, schoolchildren's mean accuracy for Go and noGo trials collapsed together (*M*= 41.3%, *SE* = 3.2%) was significantly lower than the adults' mean accuracy (*M* = 80.8%, *SE = 3.2%*), $F(2, 144) = 48.5$, $p < .001$, $\eta^2_p = .40$. However, the two groups of children did not significantly differ from each other, $F(2, 144) = .63$, $p = .537$, $\eta^2_p = .01$. Moreover, the ratio of Fast vs. Slow Hits also did not significantly differ between the three groups, $F(2, 144) = 1.93$, $p = .148$, $\eta^2_p = .03$.

Reaction time. Mean RTs (in ms) for Hits were significantly faster for adults than traditional schoolchildren ($p_{bonferroni} < .001$), and Montessori schoolchildren ($p_{bonferroni} = .019$), $F(2, 144) = 7.67$, $p < .001$, $\eta^2_p = .10$ (see Table S2). However, the two groups of children did not significantly differ from each other ($t(144) = .88$, $p_{tukey} = .654$).

Affective Word Categorization Task

The number of trials per condition (Hit-positive, Hit-negative, FA-positive, and FA-negative) did not significantly differ between groups and conditions, $F(2, 144) = .982$, $p = .377$, $\eta^2_p = .01$ (see Table S3).

Reaction time. The ANOVA showed a significant three-way interaction, $F(2, 144) = 5.32$, $p = .006$, $\eta^2_p = .07$, corroborating the hypothesis that ACTION was differently processed at the affective level (VALENCE) depending on the GROUP (Table S4, Figure 3B). Since the accuracy in the Go/noGo Task was lower for children than for adults (see above), we also performed a control analysis to ascertain that this significant interaction was not merely conflated by this imbalance. More specifically, we selected a subset of errors in children (using the down-sampling function in R) to match their error frequency with the adults. The results of this control analysis confirmed that the three-way interaction was significant, $F(2, 144) = 4.58$, $p = .012$, $\eta^2_p = .06$. Subsequently, we assessed PM in each group separately, using a 2 (ACTION) x 2 (VALENCE) ANOVA.

Adult Participants. The main effect of ACTION was significant, $F(1, 45) = 35.4$, $p < .001$, $\eta^2_p = .44$, indicating slower RTs after FAs ($M = 755$, $SE = 27.6$) than following Hits ($M = 579$, $SE = 27.6$), and thereby indicating the presence of PES (Ullsperger, Danielmeier, et al., 2014), see Figure 3A. The main effect of VALENCE was marginally significant, $F(1 ,45) = 3.86$, $p = .056$, $\eta^2_p = .08$, the RTs for negative words ($M = 639$, $SE = 27.4$) were slightly faster than for positive words ($M = 695$, $SE = 27.4$). Importantly, the two-way interaction was also significant, $F(1, 45) = 6.39$, $p = .015$, $\eta^2_p = .12$. Post-hoc *t*-tests revealed that mean RTs for negative words was faster than for positive ones after FAs (respectively, $p_{\text{tukey}} < .011$ and $p_{Tukey} < .001$ in the control analysis), whereas RTs for negative and positive words after Hits did not significantly differ ($p_{\text{tukey}} = .973$) (see Figure 2A).

Schoolchildren Experiencing Traditional Pedagogy. The main effect of ACTION was significant, $F(1, 55) = 25.54$, $p < .001$, $\eta^2_p = .32$, showing that RTs following FAs were slower ($M = 1394$, $SE = 69.1$) than following Hits ($M = 1173$, $SE = 69.1$), indicating PES in this group as well (Figure 3A). VALENCE was also significant, $F(1, 55) = 11.88$, $p = .001$, $\eta^2_p = .18$, the RTs were faster for positive ($M = 1208$, $SE = 69.2$) than negative words ($M = 1360$, $SE = 69.2$). Importantly, the two-way interaction was also significant, $F(1, 55) = 4.57$, $p = .037$, $\eta^2_p = .08$. A post-hoc t-test revealed that RTs for positive words were significantly faster than for negative ones after Hits ($p_{\text{tukey}} < .001$), whereas RTs did not significantly differ between negative and positive words after FAs ($p_{\text{tukey}} = .877$; see Figure 2B). This finding suggests an opposite pattern for children and adults: the traditional schoolchildren showed affective priming for correct actions only, whereas adults showed affective priming for errors only.

Schoolchildren Experiencing Montessori Pedagogy. The main effect of ACTION was significant, $F(1, 44) = 27.41$, $p < .001$, $\eta^2_p = .38$, with slower RTs following FAs ($M = 1634$, $SE = 87$) than following Hits ($M = 1297$, $SE = 87$), suggesting that PES was also observed in Montessori schoolchildren (Figure 3A). The main effect of VALENCE was significant as well, $F(1, 44) = 5.591$, $p = .023$, $\eta^2_p = .11$, the RTs were faster for positive (M = 1413, SE = 84.2) than negative words (M = 1519, SE = 84.2). Unlike the traditional schoolchildren, the two-way interaction was not significant in this group, $F(1, 44) = .802$, $p = .375$, $\eta^2_p = .02$ (see Figure 2C). Accordingly, Montessori schoolchildren did not show a significant differential affective priming depending on the value of the preceding action.

Schoolchildren Experiencing Traditional Versus Montessori Pedagogy. Based on the fact that traditional and Montessori schoolchildren did not process the affective valence of the words after their correct actions in a similar fashion, we ran a mixed model ANOVA directly comparing the two groups of children in the evaluative word categorization task following Hits. This analysis confirmed that the two groups of children significantly differed from each other, $F(1, 99) = 3.99$, $p = .049$, $\eta^2_p = .04$. More specifically, whereas affective priming was significant after Hits for traditional schoolchildren ($t(99) = -4.04$, $p_{tukey} < .001$), it was not the case for Montessori schoolchildren ($t(99) = -0.60$, $p_{tukey} = .933$). When controlling for gender and SES in an ANCOVA, VALENCE was at trend level, $F(1, 94) = 3.95$, $p = .050$, $\eta^2_p = .04$. We did not add age and fluid intelligence as covariates in this ANCOVA, as they correlated with one another, and moreover, they both correlated strongly with the mean RT making the interpretation of these results difficult.

Accuracy. The ANOVA showed that the three-way interaction was significant, $F(2, 144) = 6.82$, $p = .001$, $\eta^2_p = .09$ (Table S5).

Adults Participants. The main effect of ACTION was only marginally significant, $F(1, 45) = 3.54$, $p = .067$, $\eta^2_p = .07$, showing a slightly higher accuracy following Hits (M = 87.9, SE = 2.0) than FAs (M = 83.6, SE = 2.0). VALENCE was significant, $F(1, 45) = 14.46$, $p < .001$, $\eta^2_p = .24$, with a higher accuracy for negative (M = 90.3, SE = 2.0) than positive words (M = 81.2, SE = 2.0). Moreover, the two-way interaction was also significant, $F(1, 45) = 21.49$, $p < .001$, $\eta^2_p = .32$, with a higher accuracy for negative than positive words after FAs ($p_{tukey} < .001$), but no significant difference between negative and positive words after Hits ($p_{tukey} = .956$), in line with a previous study performed on adults (De Saedeleer & Pourtois, 2016).

Schoolchildren Experiencing Traditional Pedagogy. There was a significant main effect of ACTION, $F(1, 55) = 8.06$, $p = .006$, $\eta^2_p = .13$, with a higher accuracy after Hits (M = 89.7, SE = 1.7) than FAs (M = 84.9, SE = 1.7). VALENCE was not significant ($p = .664$), nor was the interaction between VALENCE and ACTION ($p = .145$).

Schoolchildren Experiencing Montessori Pedagogy. The effect of ACTION was significant, $F(1, 44) = 4.94$, $p = .031$, $\eta^2_p = .10$, with a higher accuracy after Hits (M = 89.6, SE = 1.9) than FAs (M = 86.6, SE = 1.9). The main effect of VALENCE was significant, $F(1, 44) = 10.32$, $p = .002$, $\eta^2_p = .19$, with a higher accuracy for positive (M = 91.7, SE = 2.1) than negative words (M = 84.5, SE = 2.1). However, the two-way interaction was not significant ($p = .831$).

Discussion

In this study, we compared PM in 8-12 year old children and adults. We also tested whether the pedagogy experienced at school could modulate PM in children. Based on earlier studies performed only on adults (Aarts et al., 2012; De Saedeleer & Pourtois, 2016), we used a dual task procedure in order to derive two dissociable correlates of PM at the behavioral level: PES (suggesting an automatic attention orienting to response errors) and the affective processing of actions (suggesting that response errors are processed as negative events at the adult age). Our results showed that even though response errors led to PES in all three groups (Figure 3A), the affective processing of actions substantially differed between them (Figure

3B). More specifically, although the adult participants evaluated their response errors as negative events, no such evidence of a negative evaluation of errors was found in either group of children. Moreover, and contrary to the adults, children who experienced traditional pedagogy evaluated correct responses as positive events, while children experiencing Montessori pedagogy did not show this priming effect. Here after, we discuss the possible implications of these results, which suggest that PM is qualitatively different in children compared to adults, and that pedagogy can influence the affective processing of Hits. More generally, our results lend support to the notion that the automatic attention orienting towards response errors (highlighted by PES) and their affective processing as negative events (visible in priming) are two distinct components of PM (e.g., Koban & Pourtois, 2014).

Our results are consistent with previous studies showing that young children, like adults, systematically slow down following response errors (Smulders et al., 2016). Given that PES could reflect an automatic orienting response to deviant events (i.e., "oddball" response errors in the trial series, see Danielmeier & Ullsperger, 2011; Notebaert et al., 2009), our results suggest that this attention-based PM effect is mature in 8-12 year old schoolchildren. This interpretation is compatible with a vast literature in developmental psychology showing that the stimulus-driven attentional system (i.e. exogenous attention) is functional and active early in life, before top-down attentional control (Johnson, Posner, & Rothbart, 1991); an asymmetric development is observed between them (Farrant & Uddin, 2015). This dissociation has been confirmed across many modalities and tasks, including language processing (de Diego-Balaguer, Martinez-Alvarez, & Pons, 2016). In fact, young children's attention is easily captured by salient stimuli or events in their environment (such as response errors in the present case), and more years of development are needed before the endogenous control of attention is mature (Farrant & Uddin, 2015; Wainwright & Bryson, 2002). Interestingly, we found that this behavioral adaptation following errors was not smaller or larger in magnitude for children compared to adults, indirectly suggesting that PES seen at the adult age likely reflects the operations of a core PM component that is already active early in life (e.g. Basirat, Dehaene, & Dehaene-Lambertz, 2014) and might not undergo major changes between childhood and adulthood. Moreover, since we failed to observe a significant difference in PES between the traditional and Montessori schoolchildren, it is likely that this PM component is not influenced by contextual effects, including the affective meaning of response errors (or the lack thereof), and how it is reinforced by external factors or agents depending on the specific pedagogy experienced at school.

This age-invariance of PES sharply contrasts with our findings that the affective processing of self-generated actions was significantly modulated by age. Replicating previous results found in young adults (Aarts et al., 2012, 2013; De Saedeleer & Pourtois, 2016), we showed here that response errors were aversive for them (Hajcak & Foti, 2008), even though a child-friendly version of the Go/noGo task was used and these response errors only indirectly threatened their self-efficacy (e.g., they did not entail monetary losses). Furthermore, we could rule out a speed accuracy tradeoff underlying this evaluative priming effect because the adult participants were not only faster for negative than positive words after response errors, they were also more accurate in the former case. However, and strikingly, this effect was not found in 8-12 year old children, who instead showed a selective RT facilitation for positive compared to negative words following Hits. This result suggests that, unlike adults, they processed correct actions as positive events. Consequently, our results indicate that the affective processing of actions is asymmetrical, but this imbalance takes different forms depending on age. Importantly, because the positive and negative words used as targets in our study were rated in a similar way by the children and the adults, it is unlikely that this asymmetry arose because negative or positive words were perceived as more or less negative/positive by the children compared to the adults. Instead, our results suggest that the way the correct or incorrect action preceding this word was evaluated substantially differed between the two groups.

The selective processing of correct actions as positive events in children aligns with earlier work showing a stronger impact of positive than negative feedback on learning in 8-9 year old children, with a reversal of this effect occurring later during development around 11-13 years old (van Duijvenvoorde, Zanolie, Rombouts, Raijmakers, & Crone, 2008). Additionally, this shift seems to reflect a change in what children perceive as salient during learning, as opposed to being driven by valence only (van den Bos, Guroglu, van den Bulk, Rombouts, & Crone, 2009). Accordingly, it is likely that the opposite priming effects found for children and adults in this study occurred as a result of a change through development and maturation in the saliency of the action value. Indeed, whereas children mostly assign a positive value to correct decisions, errors outweigh them for adults. However, future studies will be needed to unveil the cognitive and emotional factors that enable this profound shift in the way self-generated actions are evaluated by children versus adults.

Tentatively, the lack of distinct evaluative processing of errors in these children could potentially be explained by the fact that these events are often instrumental for learning at that age and/or these events do not pose a main threat or challenge to the self (Chrysikou et al., 2013; Chrysikou, Novick, Trueswell, & Thompson-Schill, 2011; Thompson-Schill, Ramscar, & Chrysikou, 2009). In line with this idea, it was previously found that children are actually better than adults at learning abstract causal relationships as they could more easily update their prior knowledge, and more flexibly solve problems (Lucas, Bridgers, Griffiths, & Gopnik, 2014). A greater flexibility and lower error-avoidance could therefore explain why children do not automatically assign a negative value to response errors, even though they are generating them now and then during decision-making and automatically orienting towards them after their occurrences (reflected by PES). Likewise, this specific processing style that children possess could also explain why they actually assign a positive value to correct actions, which usually translates that goal striving (i.e., an overt response in the face of an imperative go stimulus has been made in the present case) and learning were successful. Further and more generally, this specific processing style could stem from the fact that the prefrontal cortex is not fully matured yet in these children (Crone & van der Molen, 2007). As a result, evaluative processes, including those involved in action and outcome, are already functional, but they probably recruit a network of subcortical brain areas involved in reward processing (van Duijvenvoorde, Peters, Braams, & Crone, 2016), which are different than those used by adult participants.

Remarkably, and unlike PES, this priming effect was exclusively found in the children enrolled in the traditional schooling system. In comparison, Montessori schoolchildren were slower following errors, but no evidence was found that they automatically processed correct actions as positive events. This difference suggests that the automatic affective processing of actions, unlike PES, is shaped by both age and pedagogy. At that age, the way self-generated actions are assessed by peers and evaluators (e.g., school teachers) is likely to profoundly influence how they are processed along an affective dimension by the children who execute them. Because children experiencing Montessori pedagogy are usually much less confronted with evaluative feedback and reinforcers for their actions than those experiencing traditional pedagogy (Lillard, 2013; Lillard, 2012; Rathunde, 2001; Rathunde & Csikszentmihalyi, 2005), it is possible that their actions acquire less specific affective values, as our results indirectly suggest . We thereby contend that the difference in affective priming found between Montessori versus traditional schoolchildren could stem from a differential reinforcement learning (RL) effect. Although it is speculative at this stage, it is feasible that pedagogy shapes PM by influencing specific RL parameters. In this perspective, it appears relevant to consider the difference between model-free and model-based RL (Dolan & Dayan, 2013; Glascher, Daw, Dayan, & O'Doherty, 2010; Neftci & Averbeck, 2019). In the latter case, the algorithm uses the transition (and reward function) to estimate the optimal policy. In the former case, these dynamics of the environment are not considered. In adults, it has been shown that this framework is extremely valuable as it can account for a wide range of phenomena during RL, including modulatory effects of feedback types or rewards (Mattar, Thompson-Schill, & Bassett, 2018). Accordingly, it would be extremely informative in future studies to more directly link changes in PM with possible alterations of specific RL parameters (using computational modelling methods for example) in order to obtain a more mechanistic understanding of how development and prefrontal cortex maturation could influence it. In this context, it is noteworthy that despite the lack of evaluative priming for correct actions, the Montessori schoolchildren nevertheless showed a higher accuracy for positive than negative words, which was not found in schoolchildren experiencing the traditional pedagogy. This result is compatible with previous findings showing that Montessori children can exhibit a bias for positive emotional stimuli in the environment (see Denervaud, Mumenthaler, Gentaz, & Sander, 2020). As our results suggest, this bias does not seem to encompass the implicit evaluative processing of self-generated actions as good or bad and could presumably be specifically present for external stimuli. Further research is needed to corroborate a possible dissociation between the processing of internal versus external emotional events in Montessori schoolchildren.

A few limitations warrant comment. First, we used a child-friendly version of the dual task previously devised for adult participants (Aarts et al., 2012), and as a result, we only had a limited number of trials per condition. Importantly, a control analysis (see Results) showed that the different affective processing of actions was not due to the imbalance in the number of trials between adults and children. Moreover, this imbalance did not influence PES. A way to overcome this limitation in future studies would be to increase the amount of trials, although this might be detrimental to the participants' selective attention or task's involvement. Second, we performed a cross-sectional study comparing children to adults, but it appears important to assess how PES and the evaluative processing of actions could change as a function of prefrontal cortex maturation, which would require the use of longitudinal studies and developmental trajectories (e.g., from 8 to 14 years old). Third, there might be a selection bias in our sample as we chose, for practical reasons, schoolchildren experiencing the Montessori pedagogy exclusively from private schools. In contrast, schoolchildren experiencing the traditional pedagogy attended public schools, where practices regarding grades and formal assessments are quite homogenized due to local policies. Accordingly, it remains to be established whether Montessori pedagogy as such or alternatively, other variables associated with the private schooling system, yields a differential affective processing of (correct) actions in children. A way to address this limitation would be to use the same experimental design employed in this study to compare Montessori children to children enrolled in other private schools experiencing a different type of pedagogy. In the same vein, it might also be valuable to consider parental attitudes and some specific education doctrines in future studies, as these variables might also influence the way actions, and more specifically, response errors are appraised by children and in turn influence their behavior. Finally, for the adults, we did not measure their socio-economic status and fluid intelligence, nor the specific pedagogy they had experienced at school. Accordingly, it appears important to replicate in future studies the current dissociation found between adults and children when the affective processing of actions is considered, and to preferably measure and model the influence of these variables in all groups.

To conclude, our findings shed new light on PM in children, and more specifically, on two fundamental components that underlie this important cognitive ability. Like adults, 8-12 year old children automatically orient their attention towards response errors, as reflected by PES. However, our results suggest that unlike adults, children did not automatically evaluate response errors as negative events. Instead, our results suggest that schoolchildren experiencing traditional pedagogy – but not Montessori— evaluated correct actions as positive events. All in all, these results suggest that PM is composed of an age-invariant component that allows individuals to orient attention towards (deviant) errors, while the affective evaluation of their actions is shaped by both development and pedagogy. This experience-dependent modulation may allow children, as well as adults, to assign value to actions in a flexible and context-dependent fashion, and ultimately, foster goal-adaptive behavior in an ever-changing environment.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

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

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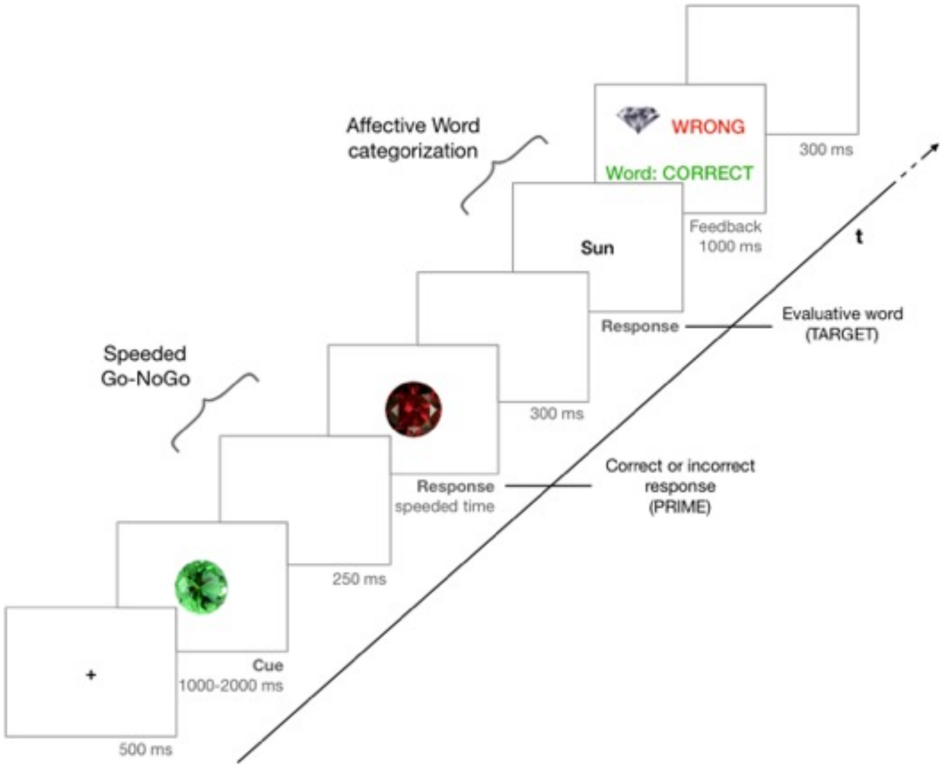

Figure 1 ***Evaluative priming task.*** During each trial, participants performed two tasks: first, a speeded Go/noGo task (that led either to correct or incorrect responses), followed by an affective word categorization task (based on positive and negative words), serving respectively as primes and targets in an evaluative priming procedure.

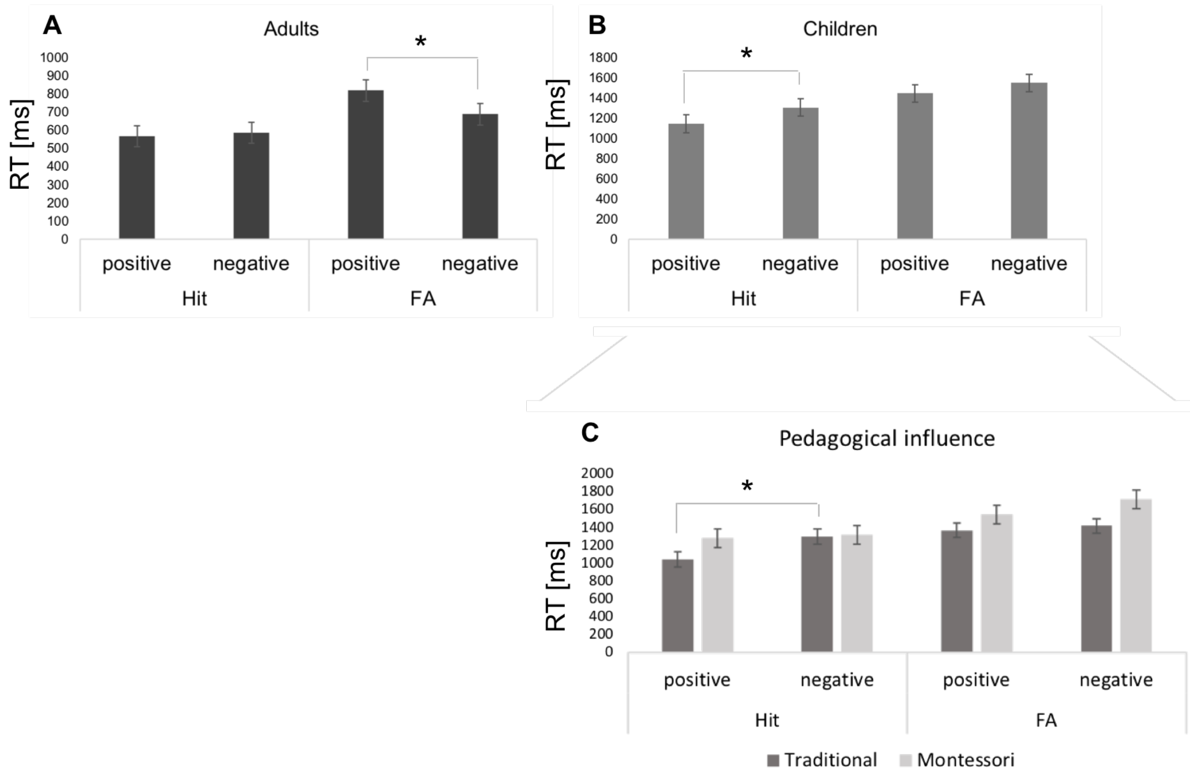

Figure 2 ***Affective word categorization task.*** Mean RTs for (A) adults and (B) children. (C) Children were split into two groups, according to the pedagogy they experienced, either traditional or Montessori. RT stands for Reaction Time, expressed in milliseconds (ms); error bars correspond to the standard error of the mean.

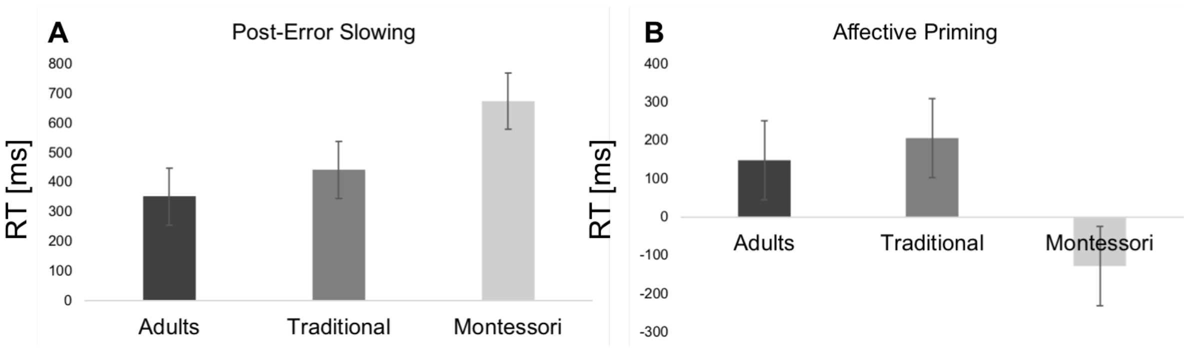

Figure 3 ***Summary of the main results.*** (A) PES, computed as (RT_{FA}-RT_{Hit}), did not significantly differ between the three groups. (B) In comparison, affective priming did. For visualization purposes, it is here computed as ($RT_{Hit\ Neg}$ + $RT_{FA\ Pos}$)-($RT_{Hit\ Pos}$ + $RT_{FA\ Neg}$), where the two congruent conditions are subtracted from the two incongruent ones. Congruency refers to the association in terms of valence between the action (prime) and the word (target). RT stands for Reaction Time expressed in milliseconds (ms); error bars correspond to the standard error of the mean.

	Schoolchildren Group				
	M	T	*t* or X^2	*p*-value FDR corrected	Cohen's *d*
n (girls)	45 (17)	56 (29)	3.40	0.13	
Age [years]	10.3 (1.2)	10.5 (1.1)	0.82	0.42	0.16
min, max	8.31-12.8	8.5-12.8			
SES [au]	7.10 (0.8)	6.77 (1.1)	1.69	0.13	0.34
Fluid intelligence [score]	34.1 (1.6)	33.4 (2.3)	1.78	0.13	0.35

	Adult Group
n (women)	46 (30)
Age [years]	28.0 (9.4)
min, max	20-40

Note. Mean and SD. Au = arbitrary unit, M=Montessori schooling background T=traditional schooling background.

Table 1 Descriptive statistics of demographic and socio-economic variables, and group comparisons.

SUPPLEMENTARY MATERIAL

Positive targets		**Negative targets**	
Ami (friend)	Liberté (freedom)	Cauchemar (nightmare)	Maladie (disease)
Blague (joke)	Paix (peace)	Chagrin (grief)	Malheur (misfortune)
Bonheur (happiness)	Paradis (paradise)	Diable (devil)	Méchanceté (wickedness)
Cadeau (gift)	Plaisir (pleasure)	Douleur (pain)	Peur (fear)
Chance (luck)	Rêve (dream)	Enfer (hell)	Regret (regret)
Fête (party)	Rire (laugh)	Fatigue (tiredness)	Souffrance (misery)
Humour (humor)	Soleil (sun)	Guerre (war)	Tristesse (sadness)
Joie (joy)		Larme (tear)	

Table S1 Target words selected from the Affective norms for French words rated by children and adolescents (FANchild) (Monnier & Syssau, 2017)

Descriptives

	Group	**Hit**	**Correct rejection**	**Miss**	**FA**	**Mean Accuracy**
Mean responses (SD) [%]	Adults	100	81.4 (12.4)	0.00	18.6 (12.4)	90.7 (6.2)
	Traditional	84.8 (19.9)	61.3 (20.3)	18.2 (9.6)	38.7 (20.4)	73.0 (13.5)
	Montessori	81.0 (20.1)	58.4 (20.8)	19.6 (9.8)	41.6 (20.8)	69.7 (12.9)
RT (SD) [ms]	Adults	282 (53)				
	Traditional	370 (135)				
	Montessori	350 (135)				

Table S2 Descriptive statistics of the Go/noGo task.

Descriptives

	Group	NB_HitPos	NB_HitNeg	NB_FAPos	NB_FANeg
Mean (SD)	Adults	34.6 (3.51)	33.4 (3.51)	3.13 (1.34)	4.04 (2.71)
	Traditional	35.7 (4.79)	32.3 (4.79)	6.23 (3.29)	6.79 (3.61)
	Montessori	36.6 (3.91)	31.4 (3.93)	7.40 (4.01)	6.38 (3.20)

Table S3 Number of trials per condition included in the analyses.

Within Subjects Effects

	Sum of Squares	df	Mean Square	F	p	partial η²
ACTION	96.371	1	96.371	78.418	< .001	0.353
ACTION ✻ Group	40.671	2	20.336	16.547	< .001	0.187
Residual	176.967	144	1.229			
VALENCE	0.122	1	0.122	0.112	0.739	0.001
VALENCE ✻ Group	15.892	2	7.946	7.252	< .001	0.092
Residual	157.775	144	1.096			
ACTION ✻ VALENCE	8.254	1	8.254	6.540	0.012	0.043
ACTION ✻ VALENCE ✻ Group	**13.420**	**2**	**6.710**	**5.317**	**0.006**	**0.069**
Residual	181.727	144	1.262			

Note. Type 3 Sums of Squares

Between Subjects Effects

	Sum of Squares	df	Mean Square	F	p	partial η²
Group	48.3	2	24.13	5.65	0.004	0.073
Residual	615.3	144	4.27			

Note. Type 3 Sums of Squares

Table S4 Results of the omnibus ANOVA performed on the mean z-RTs (affective word categorization task).

Within Subjects Effects

	Sum of Squares	df	Mean Square	F	p	partial η²
ACTION	0.23416	1	0.23416	14.6871	< .001	0.093
ACTION ✻ Group	0.00851	2	0.00426	0.2670	0.766	0.004
Residual	2.29585	144	0.01594			
VALENCE	9.35e-4	1	9.35e-4	0.0314	0.860	0.000
VALENCE ✻ Group	0.62825	2	0.31413	10.5406	< .001	0.128
Residual	4.29145	144	0.02980			
ACTION ✻ VALENCE	0.33385	1	0.33385	16.4932	< .001	0.103
ACTION ✻ VALENCE ✻ Group	**0.27602**	**2**	**0.13801**	**6.8182**	**0.001**	**0.087**
Residual	2.91479	144	0.02024			

Note. Type 3 Sums of Squares

Between Subjects Effects

	Sum of Squares	df	Mean Square	F	p	partial η²
Group	0.0531	2	0.0265	0.519	0.596	0.007
Residual	7.3672	144	0.0512			

Note. Type 3 Sums of Squares

Table S5 Results of the omnibus ANOVA performed on the accuracy score (% correct affective word categorization).