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PAPER**Developmental Science**

Developmental changes in impulse control: trial-by-trial EMG dissociates the evolution of impulse strength from its subsequent suppression

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Goal-oriented behavior can be disrupted by irrelevant information that automatically activates incorrect responses. While behavioral errors reveal response capture in such situations, they are only the tip of the iceberg. Additional subliminal activations of the incorrect responses (partial errors) can be revealed on correctly responded trials thanks to electromyography (EMG). In the current study, for the first time, EMG recorded in children was combined with distributional analyses. This allowed to investigate the properties of incorrect response activations and to highlight developmental changes in impulse control. A sample of 114 children aged 6 to 14 years was studied. Children performed a Simon task in which the irrelevant stimulus-position automatically activates a response that might be compatible or incompatible with the correct one. On incompatible trials, the automatic response activation must be overcome by controlled response selection. As previously observed in adults, our approach revealed the presence of an automatic EMG activation of the incorrect response elicited by the irrelevant stimulus dimension. Further, it revealed another independent source at the origin of incorrect response activations: the tendency to guess for response alternation. Both sources increased the frequency of early incorrect EMG activations, indicating impulsive responding. In addition, the influence of both sources decreased with increasing age. Thus, development is marked by improved ability to manage distractibility on the one hand and decreased tendency to rely on a guessing strategy on the other.

KEYWORDS

impulse control, susceptibility to interference, EMG, partial errors, distributional analysis, response transition

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1 | INTRODUCTION

Goal-directed behavior can be challenging when different aspects of the external world are processed in parallel and result in the activation of multiple ways of acting. Some prepotent information, although irrelevant, can lead to the activation of inappropriate responses and thus to impulsive behavior, conceived as a tendency to react prematurely to environmental stimulations, even when not relevant (Dalley et al., 2011). It has been previously reported that as children grow older, they better control the interference of irrelevant information through increased efficiency of inhibitory processes (Cragg et al., 2009; Cragg and Nation, 2008; Erb and Marcovitch, 2018). However, impulse control depends on both the strength of the impulse, and on the inhibitory capacity (Aron, 2011), these two processes being experimentally dissociable (Spieser et al., 2015; Fluchère et al., 2018; Korolczuk et al., 2020). This study aimed at revealing how these two components of impulsivity evolves during childhood. The approach that combines electromyography (EMG) and distributional analyses was applied, for the first time in children, in order to provide a fine-grained picture of the processes involved in the development of interference control.

Interference control is most often studied through so called conflict-tasks, such as the Stroop (Stroop, 1935), the flanker (Eriksen and Eriksen, 1974) or the Simon task (Simon, 1990). All these tasks share the same fundamental characteristics: targets have task-relevant and task-irrelevant dimensions that are related to the same response (compatible condition) or to different responses (incompatible condition). The robust observation is that incompatible targets induce longer RTs and higher error rates than compatible targets, the so-called interference effect. According to dual-route models (De Jong et al., 1994; Kornblum et al., 1990), the irrelevant stimulus dimension is processed through a fast and automatic route leading to early activation of the corresponding response that is incorrect in case of incompatible targets. The relevant stimulus dimension, on the other hand, is processed by a slow and controlled route activating the correct response later on within the trial.

RESEARCH HIGHLIGHTS:

- The aim was to investigate developmental changes in impulse control in a cross-sectional sample of 6 to 14 years old children.
- Electromyographic (EMG) recording from responding hands was coupled with the distributional analyses of the latencies of correct and incorrect EMG activations.
- Young children revealed more fast automatic incorrect response activations prompted by irrelevant stimulus information and by expectancies about probability of response alternation than older children.
- Development is marked by a decrease in the tendency to impulsively react to event in the environment.

The interference effect in conflict tasks has generally been shown to decrease with age during childhood (e.g., Davidson et al., 2006; Ikeda et al., 2014; Pozuelos et al., 2014; Wright et al., 2003). However, the precise age at which control efficiency reaches adult level varies considerably across studies. There might be two main reasons for these inconsistencies. First, different variants of conflicts tasks are used interchangeably, and it is more or less implicitly assumed that the same processes are at play in the different tasks and hence that their development path is the same. Second, the often-restricted age-range may obscure the developmental picture. To clarify this picture, Ambrosi et al. (2020) designed an experimental procedure allowing the three main conflict tasks (Stroop, flanker, and Simon tasks) to be directly compared through the use of the same stimulus sets in all three tasks and by administering them to a large cross-sectional sample of children from 5 to 14 years old and to a group of adults. Moreover, they used conditional accuracy functions (CAF; response accuracy plotted as a function of response latency, see below) to delineate within-trial dynamics of the interference effect. Ambrosi et al. (2020) showed important developmental variations in CAF pattern between the three tasks. In the Simon task, even the 5-year-old children group showed an adult-like pattern: CAFs showed a drop

in accuracy for shortest response latencies on incompatible trials and a rapid increase in accuracy for longer response latencies up to nearly 100 % (e.g., van den Wildenberg et al., 2010). The drop in accuracy on fastest trials is interpreted as resulting from early automatic activation of the incorrect response induced by irrelevant stimulus dimension. The increase in accuracy on slower trials, on the other hand, is interpreted as later suppression of the incorrect response and/or the activation of the correct one. In the Stroop task, maturation of interference control revealed most protracted. Although incompatible trials were less accurate than compatible trials in general, they were also characterized by the absence of a clear drop of accuracy for the shortest RTs in the two youngest groups, and by the absence of a performance ceiling for the longest RTs in children up to 13-years-old. The developmental effect in the flanker task was the least consistent. The authors concluded that each task involving a unique type of conflict was characterized by a distinctive developmental pathway of performance.

Most striking, however, was the lack of developmental effects on the Simon task. Previous studies were inconclusive as to the maturation of interference control in this task, with age-related reduction of the interference effect obtained by Davidson et al. (2006) and lack of thereof observed by Sheridan et al. (2014). The CAF analysis carried out by Ambrosi et al. (2020) speaks in favor of a lack of developmental changes in this task. Yet, overt response accuracy is only the tip of the iceberg, and its analysis hides covert incorrect response activations.

To reveal such incorrect response activations, Erb and Marcovitch (2018, 2019) used a reach-tracking version of the Simon task. Participants were asked to produce a reach movement toward one of two lateralized targets. Stimulus shape determined which of two targets had to be reached, whereas its position was irrelevant. Their task allowed early threshold adjustment to be separated from the later controlled selection process. The degree to which response tracks deviated from the direct path to the selected target, was higher in incompatible than compatible trials with the largest deviations for youngest children (6-8 years old), intermediate for older children (10-12 years old) and the smallest for adults. This sug-

gests that the ability to resist the irrelevant stimulus dimension and make a controlled selection of the correct response improves with age.

An alternative approach, developed in adults, is to record electromyographic (EMG) activity of the muscles involved in the responses, as it provides a direct measure of motor activity at the effector level. Typically, a large EMG burst is detectable just before the response button press. Additionally, EMG reveals sub-threshold muscles contractions that do not lead to the response button press (Figure 1). When adults perform conflict tasks, these sub-threshold EMG bursts, called partial errors, are present predominantly on incompatible trials on the hand related to the incorrect response (Coles et al., 1985; Burle et al., 2002; Hasbroucq et al., 2001). Partial errors are interpreted as reflecting automatic response activation by irrelevant stimulus dimension, that is further suppressed. Inefficient or absent suppression of partial errors eventually results in pressing the incorrect response. In case of successful suppression, partial errors are followed by correct response activation.

Such partial errors allow two complementary measures to be extracted, which index the strength of the impulse and the effectiveness of the inhibition, respectively. First, the distribution analysis of adults' incorrect response activations (both corrected and uncorrected, i.e., partial and full errors) as a function of their latencies (EMG- CAF) (van den Wildenberg et al., 2010; Ramdani et al., 2015) provides an estimation of the strength of the impulse, independently of the success of the subsequent attempt to inhibit (see below for more details).

Second, one can compute the "Correction ratio" (CR) defined as:

$$CR = \frac{N_{pe}}{N_{pe} + N_{er}} \quad (1)$$

where N_{pe} is the number of partial errors, and N_{er} the number of committed errors. In other words, CR corresponds to the number of corrected incorrect response activations divided by the total number of incorrect response activations, corrected or not. Thus, it is a measure of correction efficiency. These two measures are formally independent, and it has indeed been shown that they can

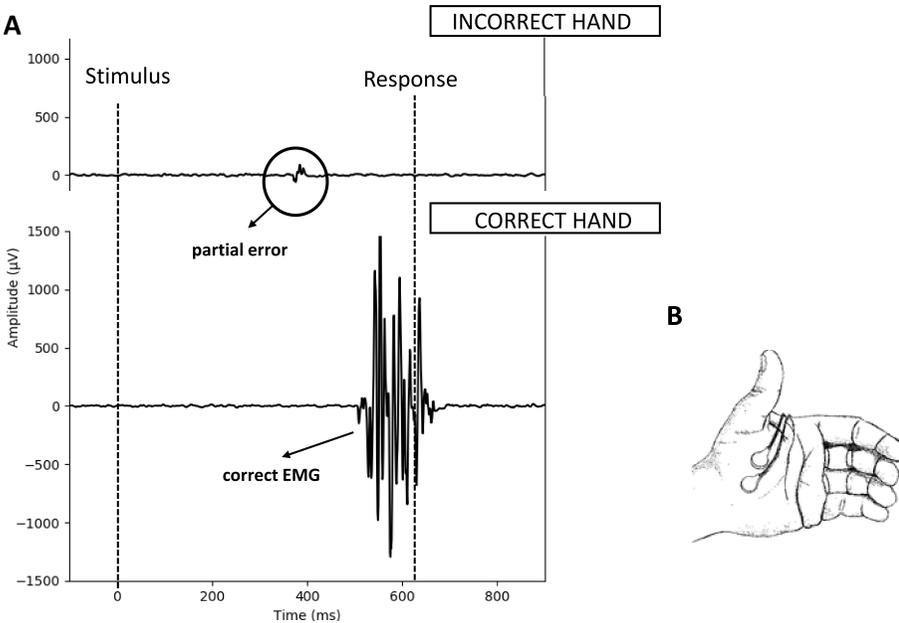


FIGURE 1 A: An example of a trial with partial error: small EMG activity apparent on the hand related to the incorrect response is present shortly before the EMG burst on the hand related to the correct response that leads to a response button press. B: placement of electrodes on pollicis brevis for EMG recording.

be manipulated selectively (e.g., Fluchère et al., 2018; Kolarczuk et al., 2020).

Although EMG offers a unique opportunity to investigate response-related processes, it has been very rarely recorded in children. van de Laar et al. (2012) recorded trial-by-trial EMG signal in two groups of children (8 and 12 years-old) and a group of adults. The participants responded with their left or right hand depending on the direction pointed by the centrally presented arrow. Van de Laar et al. observed that partial errors were more frequent in children than in adults, however they were not different in the two groups of children. Unlike in conflict tasks, targets used in this study did not have any irrelevant stimulus dimension that could lead to automatic activation of the incorrect response, suggesting other sources of incorrect response activations. Killikelly and Szűcs (2013), on the other hand, recorded EMG in adolescents (16-17 years old) and young adults (23-30 years old) performing the stimulus-response compatibility task (Fitts and Deininger, 1954; Fitts and Seeger, 1953). However,

they did not quantify EMG activity on a trial-by-trial basis, preventing the analysis of partial errors. Indeed, partial errors occur at different time points after stimulus presentation and are present only on a subset of trials (15 -20 %; Burle et al., 2002) and are therefore not apparent in the averaged EMG signal.

In the present study, partial errors were studied with EMG measured in the standard Simon task, so that the amount of incorrect response activation and the efficiency of the further incorrect response correction could be quantified separately through partial errors detected on a trial-by-trial basis coupled with distribution analyses.

2 | METHOD

2.1 | Participants

One hundred and forty-eight children participated in the study. The data from 34 children were not included in the analyses due to following reasons: technical problems

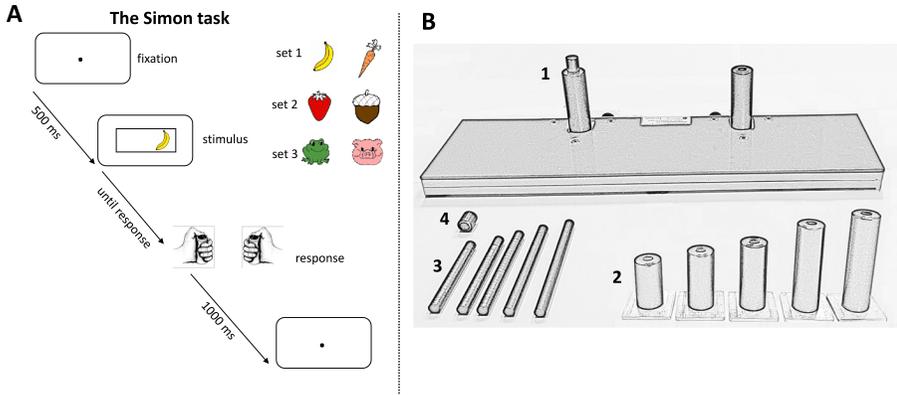


FIGURE 2 The Simon task. On the left: temporal sequence of events within one trial and three stimulus sets used in the task. On the right: response device with response buttons mounted on cylindric handgrips (1B-2), that contained another thin cylinder (1B-3) touching force sensors located in the board (1B-1). The size of the handgrip and of the inner thin cylinder were chosen for each child to fit his/her hand size. The top of the thin cylinder was covered by a cap (1B-4) to increase the pressing comfort.

related to EMG recording (12), abortion of the task (4) and noisy EMG data (18). Details about the final cross-sectional sample of 114 children are provided in Table 1. Participants were recruited in the primary and secondary French schools. They provided verbal consent and informed written consent was obtained from children's legal guardians. The study was approved by the head of the regional ethics committee ([name deleted to maintain the integrity of the review process]). All participants had normal or corrected-to-normal vision and normal color vision.

2.2 | Material and Apparatus

The experiment took place in a school building, in a room adapted to the experimental needs. Children were tested individually during a single session of about 45 min. The children performed a computerized task controlled by PsychoPy software (Peirce, 2007): the stimuli were presented on a monitor screen (with a distance of 50 cm from participant's face). The three sets of stimuli ($3.6^\circ \times 3.6^\circ$) introduced by ([name deleted to maintain the integrity of the review process]) were used: these were cartoonish images (see Figure 2A) of a banana and of car-

TABLE 1 Descriptive statistics. Characteristics of the participants.

Group (age in years)	Number of participants	Sex (number of boys)	Mean age (SD) in months	Percent of rejected trials	Correction Ratio (mean)
6	14	8	81.1 (4.0)	3.5	0.78
7	12	7	93.3 (3.3)	3.5	0.75
8	15	8	103.7 (3.0)	2.8	0.73
9	13	7	116.6 (4.3)	2.3	0.75
10	11	6	129.2 (3.6)	2.1	0.74
11	12	6	138.1 (4.0)	3.0	0.71
12	12	6	150.3 (3.1)	2.4	0.75
13	12	6	164.3 (3.6)	2.2	0.64
14	13	6	173.3 (3.5)	2.3	0.67

rot (1st set), a nut or a strawberry (2nd set), and a frog or a pig (3rd set). Stimuli were presented with an eccentricity of 3.9° from the central fixation point (0.5°) within a black frame ($12.1^\circ \times 3.9^\circ$) displayed on the gray screen. Children provided their responses via a response device that was adjusted to their hands (Figure 2B). Size-adjustable response buttons were mounted on cylindrical handgrips, that contained another thin cylinder touching force sensors located on the board. Pressure on the thin cylinder was directly transferred to the force sensors that recorded the force of the response button presses. The top of the thin cylinder was covered by a cap to increase the pressing comfort. Before the experiment, one of five heights of the handgrip and the thin cylinder that best matched the size of participants' hands were chosen. Participants were instructed to keep their thumbs on the response buttons during the entire task and to respond as quickly and as accurately as possible.

2.3 | Procedure

Two experimenters accompanied each child during the experiment. A child-friendly version of the Simon task (Simon, 1990; Figure 2A) was administered with three blocks of trials, each containing a different stimulus-set. The block order was counterbalanced between children. At the beginning of each trial, a fixation point was presented for 500 ms and was followed by a centrally displayed black frame containing a target-stimulus on its left or right side. Target remained on screen until a response was given. Next trial started 1 s later. The participants were asked to discriminate between two target-colors and to press accordingly one of two response buttons (the left or right one). The mapping between the target-color and the response-side was counterbalanced between participants. The participants were also instructed that the position of the target is irrelevant. In the compatible condition, the target position was ipsilateral to the required response, and in the incompatible condition the target was presented contralateral to the required response. Both conditions were fully randomized and equally likely.

The experimental task consisted of three blocks of

100 trials. Participants took longer breaks between blocks, and additionally they had short breaks after each series of 25 trials. Blocks started with the instruction indicating the mapping between target-color and response-side. The instruction was followed by two trainings (36 trials in total) during which children learned the task. During the first training auditory feedbacks (two contrasting sounds for correct and incorrect response) informed about response accuracy. The next trial was initiated by the experimenter, who re-explained the task in case a participant committed an error. The second training was feedback-free: next trials started independently of whether the correct response was given in the preceding trial. After each training, participants received information about the number of errors they committed. This information was displayed on the screen and explained verbally by the experimenter.

2.4 | Electrophysiological recording and processing

EMG was recorded with Ag/AgCl active flat electrodes (pre-amplified electrodes, Biosemi Inc., Amsterdam, The Netherlands). In order to record from the flexor pollicis brevis of each hand (Figure 1B), two electrodes were placed on the thenar eminence of each thumb with the maximal possible distance apart (1 cm at least). EMG activity was digitized online (sampling rate: 2048Hz; analog bandwidth limit: -3 dB at $1/5$ th of the sampling rate) with use of the BioSemi Active-Two system (Biosemi Inc., Amsterdam, The Netherlands). The EMG signal was continuously monitored by an experimenter who tracked down the appearance of tonic muscular activity masking small task-related muscular activations. Children were asked to relax their hands whenever the tonic activity appeared increasing during the recording. The preprocessing of EMG signal started with creating a bipolar montage for left and right hand separately. To remove slow fluctuation that are unrelated to EMG activity, EMG signal was high-pass filtered at 10 Hz. The detection of the onsets of EMG bursts accompanying the execution of responses was done in two steps: first an automatic detection was performed based on an algorithm combining the variance

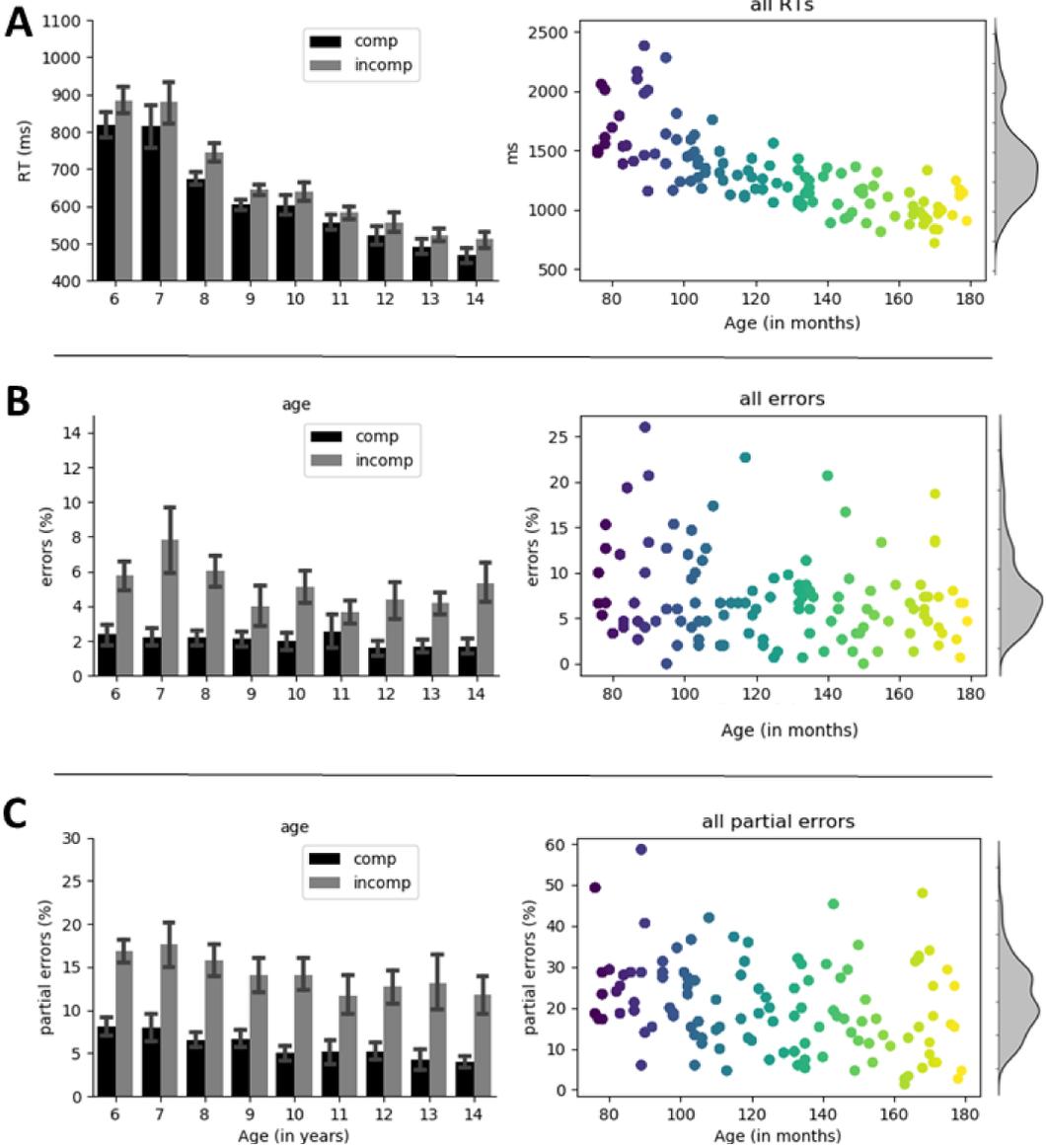


FIGURE 3 Mean values for the main dependent variables. A: RTs; B: errors and C: partial errors. On the left, data are plotted separately for compatible and incompatible trials and separately for groups based on age calculated in years (error bars represent 95% confidence intervals) for better visual inspection. On the right: (1) the scatterplots show individual data with age calculated in months (age is coded from the youngest children represented by the darkest colors to the oldest children represented by the lightest colors); (2) the kernel density estimates.

ratio (Hodges and Bui, 1996) and the “integrated profile” (Liu and Liu, 2016) as implemented in a home-made open-source software (Spieser & Burle, in preparation). These automatic detections were then visually evaluated and, if necessary, corrected by an experimenter. Such corrections are necessary mostly when there are sudden changes in the tonic muscular activity. All EMG bursts, which deviated from the baseline, were detected regardless of whether the traces corresponded to correct or to incorrect hand and independently of when in the trial they occurred. During visual inspection, the traces of all participants were inspected by one experimenter who did not know the nature of the trial (compatible vs. incompatible; correct vs. error), nor the age of the subject. Trial with one or more EMG bursts detected were segregated into three categories: pure correct trials (with one EMG burst on the correct hand), pure error trials (with one EMG burst on the incorrect hand) and incorrect–correct trials (with one EMG burst on the correct hand that was preceded by one EMG burst on the incorrect hand). These incorrect EMG bursts that preceded correct responses are called partial errors and interpreted as resulting from the initial activation of the incorrect response by the irrelevant stimulus dimension (Coles et al., 1985, Burle et al., 2002). The percentage of trials in which the incorrect response was preceded by or simultaneously activated with the correct EMG activation were very rare (0.014 % of all trials) and did not depend on age, $F(1,112) = 1.1$, n.s. All other trials, with more than two EMG bursts on either hand, and trials with noisy EMG signal were marked as unclassified and were not further analyzed. With increasing age, the percentage of unclassified trials decreased as evidenced by mixed-model ANOVAs with Compatibility (compatible and incompatible) as within-subject factor and Age (in months) as continuous factor ($F(1,112) = 21.1$, $p < .001$; from 10 % in the youngest children to 5.9 % in the oldest, mean for all participants = 8.2 %). This effect did not differ between compatible and incompatible trials ($F(1,112)=0.008$; n.s.)

2.5 | Data Analysis

The data preprocessing consisted of rejecting the first trials within each block (all together 12 trials) and RT outliers. Outliers were identified based on median absolute deviation (MAD), a correction of central tendency and dispersion that is relatively insensitive to extreme values (Leys et al., 2013; Simmons et al., 2011). For each participant and separately for the compatible and incompatible condition, all RTs inferior and superior to median plus/minus 5 times MAD value were rejected from the analysis. Based on this criterion, about 2.6% of all trials were removed. The percentage of rejected trials decreased with increasing age $F(1,112) = 8.3$, $p = .01$ (see Table 1), which was calculated with mixed-model ANOVAs with Compatibility (compatible and incompatible) as within-subject factor and Age (in months) as continuous factor.

2.5.1 | Overt performance

RT and error rates were analyzed on all trials independently of the quality of the EMG signal and number of EMG bursts (see Method for details), that is, as if no EMG had been recorded, for sake of comparison with the literature. Conditional Accuracy Functions (CAFs) were calculated separately for each participant and for compatible and incompatible trials. In order to analyze CAFs, response latencies of correct and incorrect trials were first “vincentized” (Ratcliff, 1979; Vincent, 1912, see Ambrosi et al., 2020): all RTs were sorted in ascending order and binned in five classes containing the same number of trials. For each bin, the probability of correct responses was calculated and then plotted as a function of mean response latency for this bin. The mean CAF was computed by averaging the correct responses probabilities and the mean latencies across all participants for each bin separately.

2.5.2 | EMG incorrect activations.

The partial errors rates (the percentages of trials with partial error relative to all trials with detectable EMG burst)

were calculated for each child separately for compatible and incompatible task conditions. To better assess the dynamics of incorrect response activation, we extended the CAF analysis, by taking into account the EMG activities instead of overt response (EMG-CAFs). For all analyzed trials (pure correct, pure errors and partial errors) together, we took the first EMG activity, sort them and binned them in five classes of latencies. Within each class, we measured the proportion of “correct” EMG (i.e., occurring on the hand corresponding to the correct response) and of “incorrect” ones (i.e., occurring on the hand corresponding to the incorrect response). Finally, the proportion of correct EMG activation per bin was plotted against the mean latency of the bin. As for CAF, this was done for each participant and condition of interest and averaged across participants. Note that in this analysis, incorrect EMG activations contain both latencies of partial errors and of overt errors, and they are compared to EMG latencies of pure correct trials.

Additionally, to assess the correction capacity, the correction ratio (CR) was calculated as a proportion of trials with partial errors among all trials with incorrect EMG activation (partial error trials and errors). This CR allows to quantify the ability to overcome incorrect EMG activations.

2.5.3 | Statistical Analysis

Data were analyzed with a linear model, a mixed-model ANOVA, that allows to include repeated-measurement factors and continuous factors. The mixed-model ANOVAs were run on overt performance and EMG incorrect activations respectively, for the global analyses the statistics were performed with Compatibility (compatible and incompatible) as within-subject factor and Age (in months) as continuous factor. For the analyses of distributions, mixed-model ANOVAs contained one additional within-subject factors Quintile (1st to 5th bin). All analyses were performed with Mixed Model that is part of the R module “General Analyses for linear models 2.0.0” available in Jamovi 1.6.3, an open-source software for statistical calculations based on R programming language (The Jamovi Project, 2021). Effective degrees of free-

dom were estimated using the Satterthwaite approximation method.

3 | RESULTS

3.1 | Overt performance

3.1.1 | RTs and error rates.

For RTs, the main effect of Age $F(1,112) = 159.0, p < 0.001$ and Compatibility $F(1,112) = 193.9, p < 0.001$ was observed, as well as the interaction between Age and Compatibility $F(1,112) = 15.4, p < 0.001$. Globally, RTs decreased with increasing Age, (cf. Figure 3A, right panel) and were faster on compatible than incompatible trials, with this compatibility effect decreasing with increasing Age (Figure 3A left panel). Percentages of errors was not modulated by Age $F(1,112) = 3.0, p = 0.09$; mean = 3.5%, SD = 3.6%, min = 0, max = 25 (Figure 3B left panel). The compatibility effect on errors $F(1,112) = 68.8, p < 0.001$ showed that more errors were committed on incompatible (5.0%) than compatible trials (2.0%) (Figure 3B right panel). The interaction between Compatibility and Age fell short of significance $F(1,112) = 2.7, p = 0.1$.

3.1.2 | Conditional Accuracy Function

CAF (the ratio between correct and error trials as a function of RT latencies) largely replicates the previous results (Ambrosi et al., 2020) and is therefore presented briefly. The main effect of Quintile was significant $F(4,1008) = 58.8, p < 0.001$, meaning that the probability of committing an error decreased at longer response latencies. The interaction between Compatibility and Quintile $F(4,1008) = 61.7, p < 0.001$ showed that the higher probability of committing an error on incompatible compared to compatible trials decreased with increasing response latencies. Other effects were not significant ($p' s > 0.49$). Figures presenting CAFs are included in Appendix 1.

3.2 | Incorrect EMG activations

3.2.1 | Partial error rates.

In contrast to error trials, main effect of Age on partial errors $F(1,112) = 9.0$, $p = 0.003$ showed that percentages of partial errors decreased with increasing Age (mean = 10.2%, SD = 7.8%, min = 0, max = 40; see Figure 3C left panel). There was also the compatibility effect $F(1,112) = 211.4$, $p < 0.001$ (Figure 3C right panel): the percentages of partial errors were higher on incompatible (mean = 14.4%, SD = 8.2%, min = 0.7, max = 40) than on compatible trials (mean = 5.9%, SD = 4.3%, min = 0, max = 20). However, the interaction between Age and Compatibility was not significant $F(1,112) = 0.5$, n.s. This means that the decrease of partial errors with Age was the same for compatible and incompatible trials. We shall come back on this point later.

3.2.2 | EMG-CAFs.

This analysis was run on all incorrect EMG activations independently on whether they were corrected (partial errors) or not (errors). Figure 4 presents the EMG-CAFs for each age group and for compatible and incompatible trials. Only effects related to the Quintile factor will be reported as breaking the data by quintile does not change the main effect of the other factors presented above. The main effect of Quintile $F(4,1008) = 330.9$, $p < 0.001$ showed that incorrect EMG activations were mainly observed early after stimulus onset. This is clearly seen in the initial drop of correct EMG activations on Quintile 1, where the difference between compatible and incompatible trials is also the largest and confirmed by significant interaction between Compatibility and Quintile $F(4, 1008) = 151.6$, $p < 0.001$. The interaction between Age and Quintile was also significant, $F(4,1008) = 7.0$, $p < 0.001$, as the Age effect appeared predominantly for shortest incorrect EMG activations. Unexpectedly, the interaction between Compatibility and Quintile was not modulated by Age $F(4,1008) = 0.5$, $p = 0.7$, suggesting that the developmental changes of the within-trial time course of incorrect EMG activations was not different on compatible and incompatible trials. The surprising drop of correct

EMG activations on Quintile 1 on compatible trials was further highlighted by the post-hoc analysis on the subset of compatible trials: the interaction between Age and Quintile was significant, $F(4,448) = 5.6$, $p < 0.001$ (the differences between Quintile 1 and other Quintiles (at least $p = 0.02$).

In order to explore the possibility that increased number of partial errors in younger children depended on the compatibility repetition versus alternation from the previous trial, the sequential compatibility effect was calculated using Mixed Model ANOVA with three between subject factors Current Compatibility, Previous Compatibility, Quintile and one continuous factor Age. Indeed, more partial errors were produced on incompatible trial when they followed compatible than incompatible one in general $F(1,2128) = 135.1$, $p < 0.001$. However, this effect was not modulated by Age $F(1,2128) = 2.9$, $p = 0.9$, which is in line with previous studies (Gyurkovics and Levita, 2020; Gyurkovics et al., 2020). The four-way interaction between Age, Current Compatibility, Previous Compatibility and Quintile was also not significant, $F(4,2128) = 0.8$, $p = 0.5$. Note, however, that power of this analysis is low due to complex and unhypothesized interactions.

3.2.3 | Correction ratio.

The main effect of Age on CR was close to significance $F(1,112) = 3.8$, $p = 0.056$, that is with increasing age the proportion of inhibited incorrect EMG activations decreased (means per age group are presented in Table 1). This surprising trend corresponds to the fact that younger children showed more partial errors than older children, whereas the number of errors was constant across ages. This descriptive trend appeared to be similar for both compatible and incompatible trials, as the main effect of Compatibility $F(1,112) = 0.04$, $p = 0.8$, and the interaction between Age and Compatibility were not significant, $F(1,112) = 1.3$, $p = 0.3$.

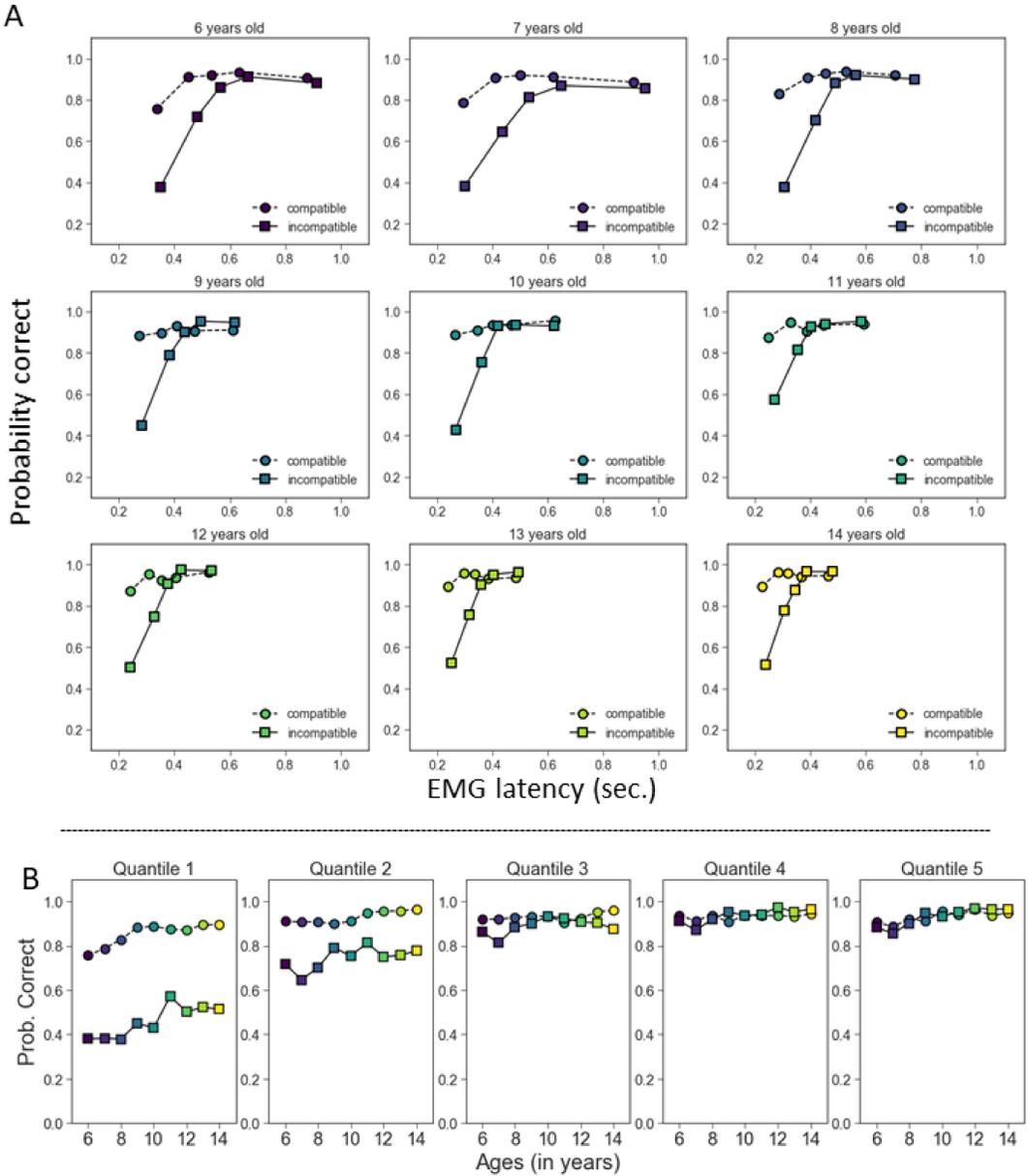


FIGURE 4 First EMG-CAFs. Panel A shows EMG-CAFs contrasting compatible (circles and dashed lines) and incompatible (squares and solid lines) task conditions for each age group separately. X-axis represent the latency (in sec.) of first EMG activations that occur within the trial and y-axis the percentage (%) of trials in which the first EMG activation was the correct one. Note the marked drop in accuracy for the fastest activations. Panel B splits EMG-CAFs and plots the proportion of correct responses for each quintile separately, as a function of age groups, for the compatible (circles) and incompatible conditions (squares). For all EMG-CAFs colors of circles and squares reflect the age group: youngest children are represented by the darkest colors and oldest children by the lightest colors.

3.3 | Response Transition effect.

The drop of accuracy for compatible trials for young children came at a surprise. While incorrect response activations on incompatible trials can be interpreted as resulting from the influence of the irrelevant stimulus location, such reasoning does not hold for compatible trials. Partial errors on these trials must have another origin, the influence of which decreases with age. To better qualify this effect, we explored the role of response transitions. Response transitions (repetitions and alternations between the previous and the current trial) may play a role in prematurely activating responses. In adults, it is well established that performance on trial n depends on the nature of trial $n - 1$ (Kornblum, 1963). However, the exact nature of the response-transition effect depends on many factors, such as the type of experimental protocol or inter-trial intervals, among others, sometimes leading to a benefit of response alternations (e.g., Bertelson, 1961; Soetens et al., 1985) and sometimes to a benefit of response repetitions (Hyman, 1953; Rapoport and Budescu, 1997).

To investigate this possibility, trials were segregated as a function of response transition from trial $n - 1$ to trial n ¹ and we investigated the impact of these transitions on children's overt performance and the number of partial errors. Note, however, that this investigation is clearly post-hoc, and dedicated experiments specifically built to test the derived hypothesis should be conducted further to confirm the present results.

3.3.1 | RTs, errors and partial errors as a function of response transitions

Mixed-model ANOVAs for each dependent variable with Compatibility (compatible and incompatible) and Response Transition (repetition and alternation) as within-subject factors and Age (in months) as between-subject factor, were run. The main effect of Response Transition was significant $F(1,336) = 103.0, p < 0.001$: response-alternation trials revealed faster than response-repetition. Response Transition effect decreased with increasing Age

$F(1,336) = 9.8, p = 0.002$. The interaction between Response Transition and Compatibility $F(1,336) = 0.3, n.s.$, and the triple interaction between Response Transition, Compatibility, and Age $F(1,336) = 0.4, n.s.$ were not significant. RTs are shown in Figure 5 in upper row.

The main effect of Response Transition was also significant for overt errors $F(1,336) = 74.0, p < 0.001$, as they were more frequent when the response repeated than when it alternated. The interaction between Response Transition and Age $F(1,336) = 5.4, p = 0.02$ revealed that the difference between response repetitions and alternations decreased with increasing age. Also, the interaction between Response Transition and Compatibility was significant $F(1,336) = 15.3, p < 0.001$: the difference between response repetitions and alternations was larger for incompatible than for compatible trials. The three-way interaction between Response Transition, Compatibility, and Age was not significant $F(1,336) = 1.6, n.s.$ (see Figure 5 middle row).

Similar results were obtained for partial errors. The main effect of Response Transition $F(1,336) = 83.3, p < 0.001$ showed that partial errors were more frequent for response repetitions compared to response alternations, with this effect decreasing with increasing Age $F(1,336) = 4.1, p = 0.04$. The interaction between Response Transition and Compatibility $F(1,336) = 12.1, p < 0.001$ revealed that Response Transition effect was larger on incompatible than compatible trials (Figure 5 bottom row). No other interaction was significant.

3.3.2 | EMG-CAFs as a function of Response Transition.

EMG-CAF analyses were performed to investigate the extent to which response transition may affect the within trial dynamics. Only effect related to the interaction between Response Transition and Quintile will be reported, as well as effects related to higher-order interactions that include these two factors, since the introduction of "quintile" does not change the effects reported above. The interaction between Response Transition and Quin-

¹Although we refer to "response transition" effect, it is to be noted that this is entirely confounded with the relevant dimension transition. The two being perfectly correlated, there is no way to disentangle them. For sake of simplicity, we will hence systematically refer to "response transition".

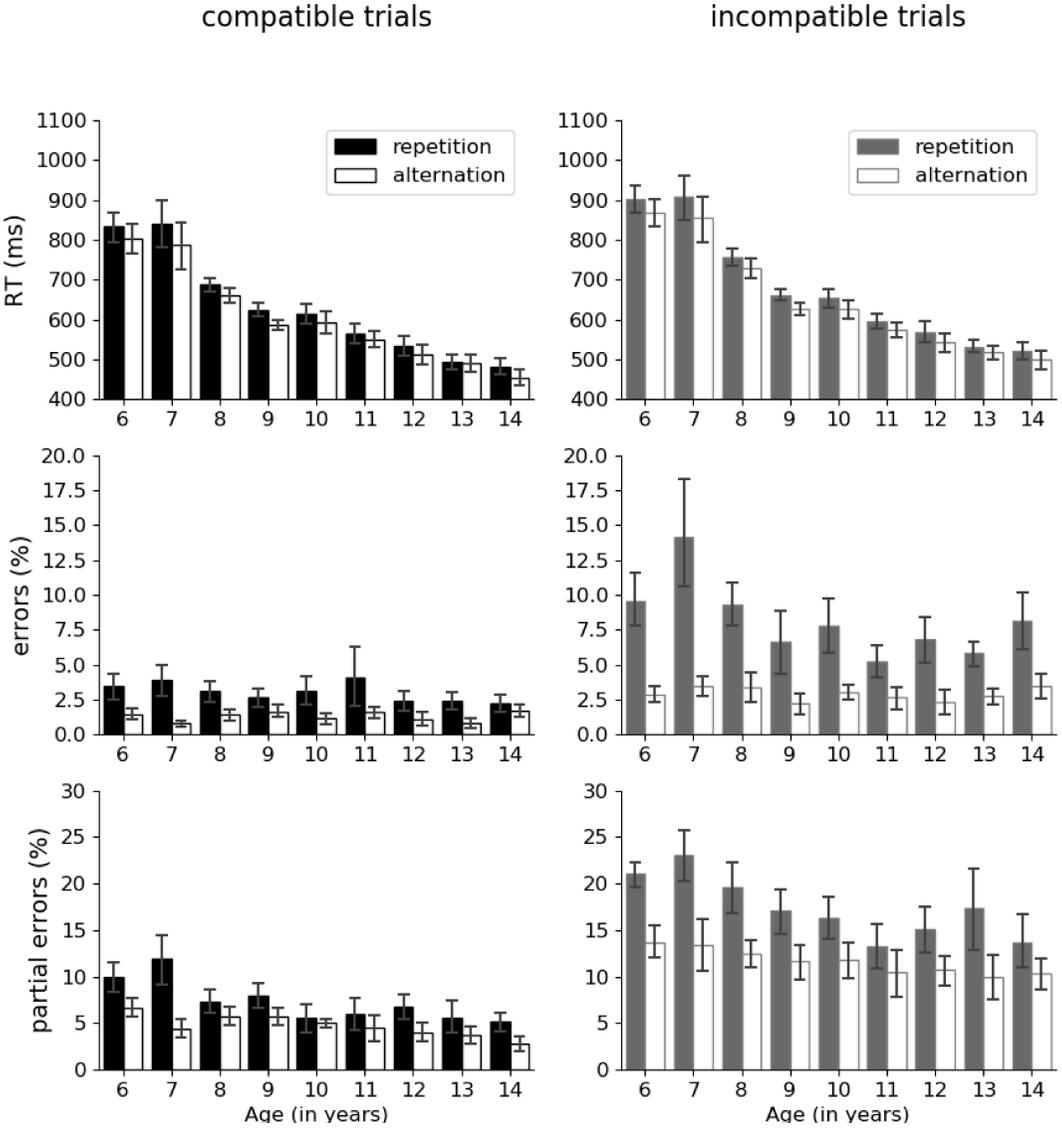


FIGURE 5 Response Transition. Response Transition effect is presented separately for compatible (left panel) and incompatible trials (right panel). The upper row presents this effect for RTs, the middle row for errors and the bottom row for partial errors. Each bar is accompanied by error bars (95% confidence intervals).

tile $F(4,2128) = 44.1$, $p < 0.001$ revealed that higher probability of incorrect EMG activation for response repetition than for response alternation was predominantly present for short latencies of EMG activations. Furthermore, the interaction between Response Transition, Quintile and Compatibility $F(4,2128) = 9.6$, $p < 0.001$ means that the larger Response Transition effect for Quintile 1 was present especially in the incompatible task condition. The interaction between Response Transition \times Quintile was not modulated by Age $F(4,2128) = 0.8$, $p = 0.5$. The EMG-CAFs are presented in Figure 6.

4 | DISCUSSION

In this study we performed a fine-grained investigation of interference control across childhood. Although the development of interference control has been investigated in numerous studies over the past few decades, it has been described primarily in terms of its overall outcome of interference control, that is the increasing efficiency of inhibitory control with age. This likely stems from the long dominant framework distinguishing three executive functions (switching, inhibition and working memory updating) identified by Miyake et al. (2000) and Lehto et al. (2003) that did not immediately invite investigation of the processes underlying each function. However, findings on inhibitory control have been partially inconsistent in terms of the time-course of development and have provided limited cues on what actually accounts for age-related improvement in inhibition tasks.

A shift in the focus of more recent developmental research on inhibitory control has shed light on these unknown aspects. Recent research has begun investigating the temporal dynamics of control processes both across- and within trials (e.g. for analyses of sequential effects, e.g., Ambrosi et al., 2016; Iani et al., 2014; Liu et al., 2018; Smulders et al., 2018, for analyses of the influence of list wide contexts on the engagement of control, e.g., Gonthier et al., 2021; Gonthier and Blaye, 2021). In order to study within-trial dynamics, different strategies have been employed. A first was the use of ERPs extracted from EEG recordings. For instance, Chevalier et al. (2014)

analyzed the interplay between the rise of the prepotent response and action decision in a go/no-go task (see also, Cragg et al., 2009). Alternatively, Erb and colleagues used reach tracking measures to dissociate a controlled selection process from a threshold adjustment process (Erb and Marcovitch, 2019). Although undeniably ERPs and tracking measures are a step forward in understanding processes at hand, they have some limits. Indeed, timing measures obtained by ERPs are largely biased by activity occurring on the earliest trials, thereby distorting these measures and making them non-comparable to RTs (Burle et al., 2008; Callaway et al., 1984). On the other hand, tracking versions of the Simon task strikingly modify the response mode used in standard versions of conflict tasks by requiring a specific move in order to reach the target response, which can affect the trade-off between deciding and acting: either starting to move only once the decision processes are finished, or initiating it before decision is completed and keep on gathering evidence during the movement time (see e.g., Battaglia and Schrater, 2007; Danev et al., 1971). The impact of such a trade-off on the profile of development is unknown (which is, per se, and interesting topic). In the present study, we used complementary, still under-used techniques in developmental studies, that does not suffer from uncertainties that have just been raised. First, we used EMG recording which reveals the presence of subliminal incorrect EMG activations (partial errors) on a substantial part of ultimately correctly responded trials in standard button press setting. Partial errors combined with overt errors, provide a better indicator of impulsive response activations (Burle et al., 2002; Spieser et al., 2015), by revealing all incorrect response activations, irrespective of their potential later correction. Second, we run analyses of distributions of correct responses (CAFs) as a function of RTs or distribution of correct-response activations (EMG-CAFs) as a function of their latencies that allow to investigate the developmental trajectory of the within-trial dynamics of correct and incorrect response activations.

Considering first traditional measures, the analysis of RTs revealed a developmental improvement of interference control through the reduction of the compatibility effect between 6 and 14 years of age. Findings

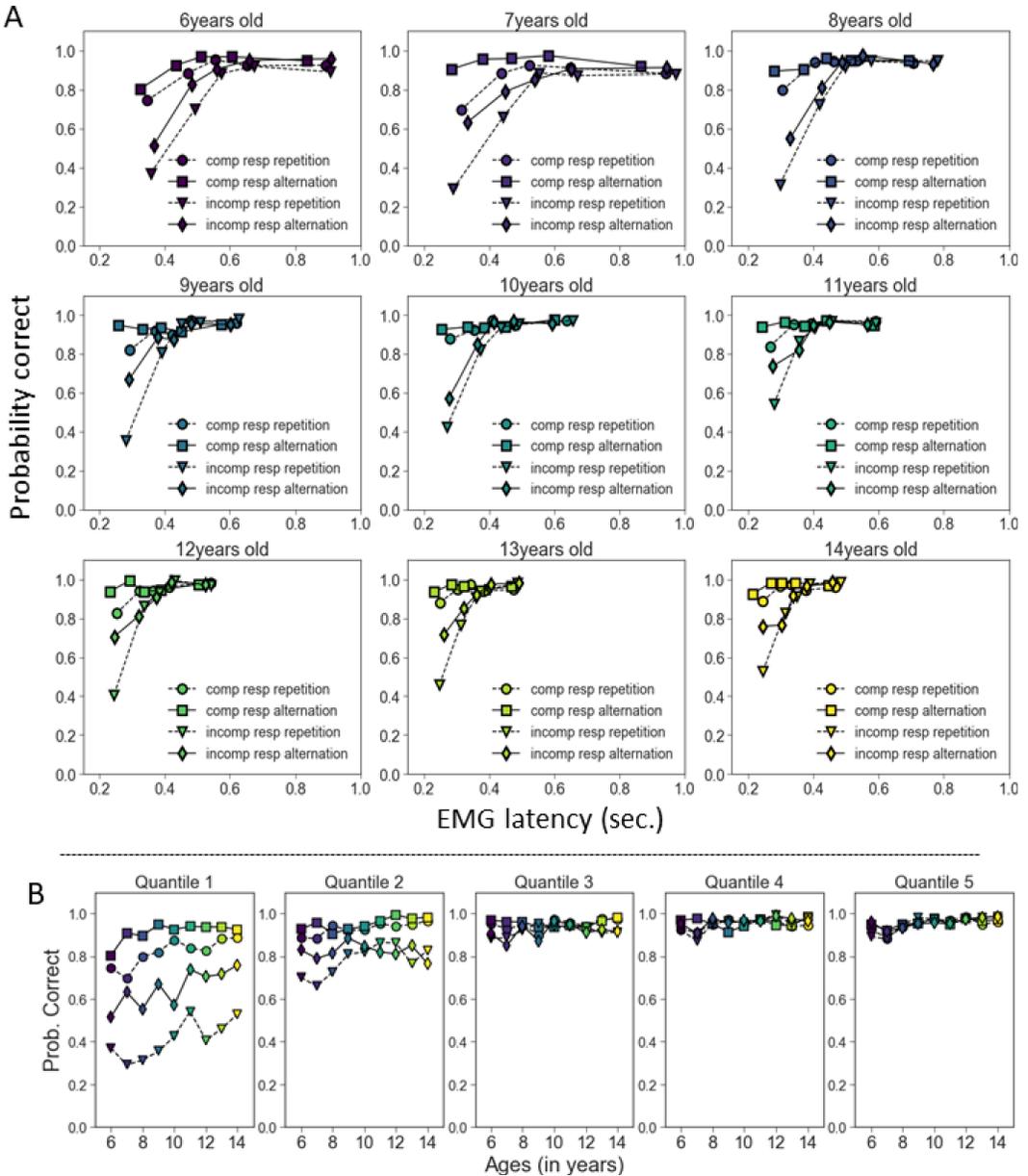


FIGURE 6 EMG-CAFs as a function of Response Transition and Compatibility. Panel A: EMG-CAFs contrasting response repetitions and alternations for compatible (circles and squares) and incompatible (triangles and diamonds) trials for each age group separately. Panel B: EMG-CAFs contrasting response repetitions and alternations for compatible and incompatible trials ask across all age groups. For all EMG-CAFs colors of circles and squares reflect the age group: youngest children are represented by the darkest colors and oldest children by the lightest colors. X-axis represent the latency (in sec.) of first EMG activations that occur within the trial and y-axis the percentage (%) of trials in which the first EMG activation was the correct one.

on errors were contrasted. Overt error rates seemed rather insensitive to progress. In contrast, partial errors on correctly responded trials decreased with age. In other words, younger children showed more frequent incorrect response activations than older children suggesting that they have a larger tendency to activate responses based on incomplete stimulus processing while the overall accuracy performance in the task was not modulated by age. This was further supported by the analysis of correction ratio: the proportion of corrected incorrect EMG activations to all incorrect EMG activations decreased with age. Taken together, if confirmed, these findings are surprising as they suggest that younger children were more successful than older children at blocking initial incorrect automatic activations in order to produce the correct response. Although surprising and counter-intuitive, this puzzling effect is actually consistent with other developmental data. First, previous developmental studies have indeed evidenced the more protracted development of proactive than reactive control (Chevalier, 2015; Chevalier and Blaye, 2022; Gonthier et al., 2019; Munakata et al., 2012). In the current study, the presence of partial errors might be interpreted as a failure in proactive inhibition and the suppression of partial errors as reactive inhibition. Second, Cragg and Nation (2008; see also Cragg et al., 2009) used a go/no-go task in which participants were required to continue pressing a home key that had to be released in order to press a target key on frequent go-trials. Thus, in the rare no-go trials, where no response was to be produced, cases where the home key was not released at all (full inhibition) could be separated from cases where it was released but the target key was not pressed (partial inhibition). Performance of 5-7 and 9-11-year-old children were compared. Whereas, as in the present study, the two groups of children did not differ in the number of errors (when the target key was erroneously pressed), younger children showed significantly more partial inhibitions than older ones. The authors interpreted these findings in terms of a longer delay in effective inhibition in the younger group. The striking similarity with the present findings obtained in a different task suggests another possible view in terms of stronger activation of the incorrect prepotent "go" re-

sponse in young children. Further investigation would however be required to dissociate these accounts.

Turning to the analyses of CAF (distribution of correct responses as function of RTs), we found that the higher error rate on incompatible trials compared to compatible ones was predominantly observed at shortest latencies. This pattern was observed in all age groups and is perfectly in line with Ambrosi et al. (2020) revealing a pattern similar to the one observed in adults as early as 5 years of age. The occurrence of errors mostly on incompatible trials and shortly after stimulus onset suggests that they are caused by a tendency to act prematurely based on the processing of the irrelevant stimulus dimension, which is the most accepted definition of impulsive responding (Dalley et al., 2011). At first sight, the lack of any age effect replicated here suggests that this tendency does not decrease with age and hence that young children are not more prone to impulsive errors, at least in this kind of conflict tasks, than older ones and possibly even adults (see Ambrosi et al., 2019, for a similar conclusion in 5-6-year-old children, based on formal modeling).

These conclusions, however, are derived from observations limited to overt behavior and findings on incorrect-response activations irrespective of their potential later correction (EMG-CAFs) revealed a partially different picture. Indeed, distribution analyses showed, as for overt errors, that the highest frequency of incorrect response activations together with the largest compatibility effects occurred predominantly early after stimulus onset and decreased later within the trial. However, contrary to overt-error rates, EMG analysis did reveal a developmental effect: the frequency of fast incorrect response activations diminished across childhood. Further, this effect did not differ between compatible and incompatible trials, suggesting the existence of two different sources underlying incorrect response activations. We now discuss the development of these two sources in turn.

The first one, the irrelevant stimulus position, transiently activates the ipsilateral response (Kornblum et al., 1990), which is the incorrect one on incompatible trials. Importantly, whereas the analyses of overt errors suggested that "impulsive" errors did not change with age, EMG analysis revealed that young children tend to react

more impulsively to irrelevant information, even if, ultimately, this does not show up on their overt error rate.

This automatic, position based, response activation does not seem to fully account for all incorrect response activations, at least for the youngest children. Indeed, in contrast to adults, children evidence short latencies incorrect EMG activations also on compatible trials. On those trials, the tendency to activate the incorrect response cannot stem from the irrelevant dimension processing as both stimulus dimensions are mapped to the same response; instead, it appeared to depend on response transitions. A post-hoc analysis clearly indicates that, in all age groups, RTs were faster when response changed between consecutive trials than when it repeated. This bias toward alternation was also observed in the form of increased errors and partial errors for response repetition trials (that is more “alternation” response activations). Moreover, the difference between repetitions and alternations was largest in youngest children and decreased with increasing age. Sequential effects of this type are rarely studied in the developmental literature. However, [Erb and Marcovitch \(2019\)](#) found similar effects of response alternation facilitation in the tracking version of the Simon task and ([Erb et al., 2018](#)) in the Eriksen flanker task: the effect was larger for children than for adults. In non-conflict tasks, rare studies reported the presence of response transition effects, decreasing with age, in children ([Erb et al., 2022](#); [Fairweather, 1978](#); [Kerr, 1979](#); [Smulders et al., 2005](#)). In these studies, however, response repetitions were faster than response alternations and could be interpreted as stemming from memory-based automatic facilitation ([Fairweather, 1978](#); [Kerr, 1979](#); [Smulders et al., 2005](#)). Since the current study was not designed to examine the response transition effect, further investigations are needed to address the observed results. We can only speculate about putative mechanism responsible for response transition by considering EMG-CAF patterns. The difference in the incorrect EMG activations between response repetitions and alternations was predominantly present early within the trial. This suggests that response alternation benefit is likely due to an automatic and transient response activation, maybe even pre-activation of a response before

stimulus presentation. In other words, participants may tend to guess for response alternation and to activate responses based on their guesses. Similar evidence of a tendency to build subjective expectations that overestimate alternations over repetitions is observed in a phenomenon known as the “gambler fallacy” ([Rapoport and Budescu, 1997](#); [Wagenaar, 1972](#)). The decrease in the likelihood of such incorrect EMG activations with increasing age suggests that older children may rely to a lesser extent on this guessing strategy. More importantly, children are sensitive to sequential effects, and these effects have a greater impact on performance of younger than of older children.

To sum up, two sources of incorrect EMG activations has been identified in the current study. The former, well established in adults, is related to the processing the irrelevant stimulus dimension, while the latter is probably related to the tendency to expect response alternations. The two effects independently modulated the likelihood of acting impulsively: whereas the effect related to the irrelevant stimulus dimension was present on incompatible trials, the tendency to expect response alternation appeared for both compatible and incompatible trials. As a consequence of these two sources, the largest number of incorrect EMG activations (overt errors and partial errors) was present when both sources could be involved i.e. on incompatible trials (induced by stimulus position) when the same response repeated (induced by incorrect guess). In turn, the smallest number of incorrect EMG activations was observed when neither source could be involved i.e., on compatible trials (stimulus position related to the correct response) when the response has been changed (correctly guessed). The reliability of the independent influence of both sources was confirmed in RTs data: slowest RTs on incompatible trials with response repetition and fastest RTs on incompatible trials with response alternation. Furthermore, as revealed by the analysis of the distribution of incorrect EMG activations, both sources influenced the probability of incorrect response activations early within the trial suggesting that both contribute to impulsive responding. Interestingly, age modulates them both leading, in general, to the decrease in the tendency to react impulsively.

In conclusion, the present study sheds some new light on the development of impulse control across childhood. By lifting the veil on the dynamics of otherwise covert behavior, the joint use of EMG and distribution analyses reveals early incorrect response activations in all age groups in a larger proportion of trials than the usually considered proportion of errors. As expected, incorrect response activations were induced by irrelevant features when in conflict with the relevant ones. Novel findings revealed that response transition also induces transient incorrect response activations and that independently of the underlying source, impulsive responding decreases with age, in line with improved proactive control with age (Chevalier, 2015; Chevalier and Blaye, 2022; Gonthier et al., 2019; Munakata et al., 2012). Most importantly, the presence of these partial errors indicates that even younger children manage to correct some of these early incorrect impulses indicating efficient reactive control (in fact analysis of the CR suggests that young children tend to be even more efficient). Hence, by using a methodology in children that had proven fruitful in adults, we were able to dissociate, across a wide age span, the strength of the impulse from its subsequent inhibition, and suggest that these two processes develop at different speeds.

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Conflict of interest

Authors declare no competing interests.

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