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RESEARCH ARTICLE

The development of selective stopping: Qualitative and quantitative changes from childhood to early adulthood

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Abstract

Although progress has been made in elucidating the behavioral and neural development of global stopping across the lifespan, little is known about the development of selective stopping. This more complex form of inhibitory control is required in real-world situations where ongoing responses must be inhibited to certain stimuli but not others, and can be assessed in laboratory settings using a stimulus selective stopping task. Here we used this task to investigate the qualitative and quantitative developmental changes in selective stopping in a large-scale cross-sectional study with three different age groups (children, preadolescents, and young adults). We found that the ability to stop a response selectively to some stimuli (i.e., use a selective strategy) rather than non-selectively to all presented stimuli (i.e., use a global, non-selective strategy) is fully mature by early preadolescence, and remains stable afterwards at least until young adulthood. By contrast, the efficiency or speed of stopping (indexed by a shorter stop-signal reaction time or SSRT) continues to mature throughout adolescence until young adulthood, both for global and selective implementations of stopping. We also provide some preliminary findings regarding which other task variables beyond the strategy and SSRT predicted age group status. Premature responding (an index of "waiting impulsivity") and post-ignore slowing (an index of cognitive control) were among the most relevant predictors in discriminating between developmental age groups. Although present results need to be confirmed and extended in longitudinal studies, they provide new insights into the development of a relevant form of inhibitory control.

KEYWORDS

cognitive control, development, response inhibition, selective stopping, SSRT, strategies

1 | INTRODUCTION

Inhibition is a domain-general cognitive construct that encompasses the ability to overcome internal or external drives and to control behavior and lower-level mental processes needed to remain goal-directed (Diamond, 2013). It can be subcategorized into cognitive inhibition (the stopping or overriding of a mental process such as memories, thoughts, or perceptions) and behavioral inhibition (the stopping or overriding of a manifest behavior) (Bari & Robbins, 2013; Hung et al., 2018; MacLeod, 2007). Here we investigate the inhibition of inappropriate, no longer required responses, a form of behavioral inhibition (Bari & Robbins, 2013; Dalley & Robbins, 2017; MacKillop et al., 2016). This ability, called response inhibition, is impaired in a wide range of neurodevelopmental and psychological disorders emerging in childhood and adolescence such as attention deficit/hyperactivity disorder (ADHD), oppositional defiant and conduct disorders, eating disorders and substance abuse disorders (Bartholdy et al., 2016; Groman et al., 2009; López-Martín et al., 2015; Schachar et al., 2007). Moreover, inefficient response inhibition has been associated with poor academic and occupational outcomes, as well as with a broad range of health and behavioral problems (Diamond, 2013; Houben et al., 2014; Morgan et al., 2019).

Most studies on response inhibition have focused on the global mechanism for stopping, which involves the rapid cancellation of all motor actions in response to a single stimulus (Aron, 2011; Wessel & Aron, 2017; Wiecki & Frank, 2013). Research using standard stop-signal tasks has been crucial to elucidate the neural and behavioral mechanisms underlying this important executive function. At the neural level, *global stopping* is thought to be mediated by the hyperdirect pathway that connects the inferior frontal gyrus and/or pre-supplementary motor area directly to the subthalamic nucleus (Chen et al., 2020; Narayanan et al., 2020). This is the fastest way to stop, but leads to global cancellation of thalamocortical motor programs. In everyday life, however, situations where multiple response tendencies need to be globally stopped are rare. Instead, real-world scenarios with multiple stimuli where some responses must be suppressed while others must continue to be executed are much more frequent. Thus, there has been an increasing interest in investigating the *selective* mechanisms of stopping using more complex and ecologically valid versions of the stop-signal task (Aron, 2011). Stopping selectively probably involves brain regions beyond those activated in global stopping, including the striatum, the dorsolateral prefrontal cortex and the superior parietal cortex (Aron, 2011; Majid et al., 2013; Sánchez-Carmona et al., 2016, 2019). Indeed, it has been proposed that selective stopping may be implemented via the indirect fronto-striatal pathway rather than the hyperdirect fronto-subthalamic nucleus pathway (Aron, 2011; Majid et al., 2013; Wiecki & Frank, 2013).

Selective stopping refers both to the ability to interrupt certain responses but not others (motor selective stopping), and to the ability to cancel the response to certain stimuli but not others (stimulus selective stopping) (Verbruggen & Logan, 2017). The latter is the focus of the present study. It can be experimentally investigated using a stimulus selective stopping task, which is a modification of the traditional stop-signal task used to examine *global* stopping. In the standard stop-signal task, participants are required to respond as fast as possible to a frequent stimulus ("go"), but to cancel the response-in-progress whenever another infrequent stimulus ("stop" signal) is presented with a variable delay shortly after the go stimulus. Selectivity is introduced into the task through a third stimulus (the so-called "ignore" or "continue" signal), which is also presented just after the go stimulus with the same frequency and delay as the stop signal. Participants are instructed to ignore this new stimulus, and thus to complete the previously initiated motor response triggered by the go stimulus.

> **Research Highlights**
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> - Although the development of global stopping has been investigated, little is known about the development of selective stopping.
> - Here we investigate the qualitative and quantitative developmental changes in stimulus selective stopping in a large-scale and wide age-range cross-sectional study.
> - The ability to stop selectively to some stimuli but not others instead of stopping indiscriminately to all stimuli fully matures by early preadolescence.
> - The efficiency or speed of stopping (SSRT) continues to mature until young adulthood both for global and selective implementations of stopping.

Most of the studies that have investigated selective forms of stopping using the stimulus selective stopping task assumed that all participants interrupted their responses selectively to stop signals. However, evidence from behavioral, electrophysiological, and neuroimaging studies revealed that individuals might use different strategies to solve the task (Bissett & Logan, 2014; Sánchez-Carmona et al., 2016; Sánchez-Carmona et al., 2019; Sebastian et al., 2017). Some participants first discriminate which stimulus has been presented (stop or ignore), and then cancel their ongoing motor response if the stimulus identified was a stop-signal (*Discriminate then Stop -DtS- strategy*). Therefore, these participants perform the task as expected (i.e., stopping selectively to stop but not to ignore signals). Nonetheless, others first suppress their response indiscriminately to both stop and ignore signals and then restart it when the stimulus presented was an ignore (*Stop then Discriminate -StD- strategy*), which is not a selective implementation of stopping.

Strategy adoption can be inferred from the behavioral data by comparing mean reaction times (RT) of correct go, correct ignore and failed stop trials (see Bissett & Logan, 2014 and Figure 1). Adoption of the *StD* strategy is reflected in faster failed stop RT than correct go RT because the stop process corresponds to the lower tail of the go RT distribution, thus preserving the go context independence assumption required by current models of stopping (Bissett et al., 2021; Verbruggen et al., 2019). This assumption posits that the finishing time distribution of the go process is the same for stop and go trials, and its

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Failed stop RT < Go RT?

Ignore RT > Go RT?	Yes	No
No	independent Discriminate then Stop **iDtS**	Uncategorized
Yes	Stop then Discriminate **Std**	dependent Discriminate then Stop **dDtS**

FIGURE 1 Decision matrix used for strategy assignment of each participant based on average go, failed stop, and ignore reaction times (adapted from Bissett & Logan, 2014)

preservation is critical for validly estimating the main dependent variables of the stop-signal tasks, including the latency of the stop process (stop signal reaction time, SSRT; Bissett et al., 2021; Verbruggen & Logan, 2009). Moreover, participants using the *StD* strategy display slower correct ignore RT than correct go RT because they cancel the response non-selectively to both stop and ignore signals, and then they need to restart it when the signal identified is an ignore.

Notably, a distinction can be made in the *DtS* strategy depending on whether the context independence assumption is met. The use of the *independent DtS (iDtS)* strategy is reflected in faster failed stop RT than correct go RT (like in the *StD*, given that the finishing time of the go process is unaffected by the presence of the stop-signal), but similar RTs for correct ignore than for correct go stimuli (participants using selective strategies do not need to restart their response in ignore trials because they only stop to stop signals). In the *dependent DtS* (*dDtS*) strategy the requirement to discriminate between stop and ignore signals does interact with the go process and slows go RT when a stop signal occurs, thus violating go context independence. This results in failed stop RT which are no faster than correct go RT, and correct ignore RT which are slower than correct go RT.

Within this framework, researchers have begun to determine which factors modulate the adoption of selective versus non-selective stopping strategies. Thus, task-related factors such as signal discrimination difficulty and probability of occurrence of the signals, and individual-related factors such as genetic variations in the dopaminergic system, have been shown to influence strategy adoption in adults (Bissett & Logan, 2014; Rincón-Pérez et al., 2020; Sánchez-Carmona et al., 2021; Verbruggen & Logan, 2015). To our knowledge, only two preliminary studies have examined age-related differences in the adoption of stopping strategies during a selective stopping task (Hsieh & Lin, 2017; Rincón-Pérez et al., 2021). Whereas the former observed a similar pattern of strategy use between younger adults (20–30 years) and older adults (61–76 years), the latter found important changes in strategy adoption in middle childhood. Specifically, a greater use of selective stopping strategies and less use of the global, non-selective strategy in children aged 10–11 years compared to children aged 6–7 years was found. These results suggest that middle childhood may be a critical period of substantial development in an individual's ability to stop selectively. Still, further studies with larger sample sizes and on a wide age-range from childhood to adulthood are needed to substantiate and extend these preliminary findings. In this sense, an interesting question that remains unexplored is whether the ability to stop selectively continues to develop beyond middle childhood up until young adulthood.

Beyond identifying the strategy used to solve the task, the stimulus selective stopping task allows for the estimation of the latency of the stop process (stop signal reaction time, SSRT). Longer SSRTs are indicative of poor, less efficient response inhibition and have been found in children, adolescents, and adults with a range of disorders characterized by impulsive symptoms, including ADHD and substance abuse disorders (Crosbie et al., 2013; Rømer Thomsen et al., 2018; Smith et al., 2014; van Hulst et al., 2018). The SSRT can be derived on the basis of the horse race model (Logan et al., 1984), which posits that the go process triggered by the onset of the go stimulus and the stop process triggered by the onset of the stop signal compete regarding finishing time. When stopping finishes before going, the already initiated response is successfully suppressed, but when going finishes before stopping, the response cannot be successfully interrupted. Importantly, this model assumes independence between the stop and the go processes, which is essential for correctly estimating the SSRT and other relevant variables of stop-signal tasks (Bissett et al., 2021; Verbruggen & Logan, 2009; Verbruggen et al., 2019).

Still, some participants use a particular selective stopping strategy (the *dDtS*: Bissett & Logan, 2014; see also Verbruggen & Logan, 2015) that does not meet the context independence assumption. In these cases, the SSRT cannot be calculated through the standard procedure of using the go RT distribution. By contrast, using the ignore RT distribution has been proposed, taking into account that the validity of this procedure needs to be confirmed (Bissett & Logan, 2014). Moreover, the SSRT for an individual who uses the non-selective, global stopping (*StD*) strategy does not include the time needed to discriminate between stop and ignore signals, because perceptual discrimination occurs after the response has been interrupted. In contrast, the SSRT for an individual who adopts a selective stopping strategy (whether or not it meets the independence assumption) includes both the signal discrimination and stopping processes. This remarks the importance of identifying and categorizing the strategy adopted by each participant in developmental research on selective stopping, so that results regarding the length of the SSRT are not confounded by differences between participants in the chain of processes involved in this measure (unlike in the selective strategies, SSRT in the *StD* does not include the discrimination stage) and in the dependency/independency of the go and stop process (violations of go context independence, which are observed in the *dDtS*, influence – and may invalidate – the estimation of SSRT: Bissett et al., 2021; Verbruggen & Logan, 2009).

Developmental studies using traditional stop-signal tasks have found that SSRT becomes faster (more efficient) with increasing age throughout childhood and at a lower rate during adolescence (Tillman et al., 2007; van de Laar et al., 2011; Williams et al., 1999). The fastest SSRT values have been observed in early adulthood, suggesting that mechanisms supporting global stopping are not fully efficient until this age period. These developmental changes in SSRT fit well with the results of most cross-sectional and longitudinal studies investigating the maturation of simple or global response inhibition, which suggest increases from childhood to young adulthood in the activation of key cortical regions of the global stopping network, including inferior frontal gyrus and pre-SMA (Bunge et al., 2002; Cope et al., 2020; Durston et al., 2002; Rubia et al., 2007). It should be noted, however, that decreases and even nonlinear developmental patterns in inhibitory control activation have also been found (Ordaz et al., 2013; Paulsen et al., 2015). Developmental research on selective stopping is much more scarce and restricted to behavioral studies (Bedard et al., 2002; Kray et al., 2009; van de Laar et al., 2011). These studies suggest a decrease in SSRT from childhood to young adulthood, where selective stopping has been associated with longer SSRTs and with a slower maturation than global stopping (van de Laar et al., 2011). These conclusions, however, need to be substantiated further due to small sample sizes and especially because it has been assumed that all participants perform the task using the same strategy (i.e., stopping selectively employing the so-called *iDtS*).

The purpose of this cross-sectional study was to examine the qualitative and quantitative development of selective stopping from childhood to young adulthood. To this end, we compared the different stopping strategies used by children, preadolescents, and adults to deal with a stimulus selective stop-signal task. Selective stopping is thought to take a longer time to mature than global stopping, given that it engages a more complex neural network and a larger number of processes (Bissett & Logan, 2014; Sánchez-Carmona et al., 2021; Sánchez-Carmona et al., 2019). Thus, we expected to find a greater use of selective stopping strategies in young adults and preadolescents in comparison to children. The non-selective (global) stopping strategy seems to be rarely adopted already by children aged 10–11 years in favor of selective stopping strategies (Rincón-Pérez et al., 2021), so we did not expect to find notable differences in strategy use in later developmental periods. Moreover, we investigated whether the developmental trajectories of SSRT are similar between the different stopping strategies. We expected to find a progressively greater efficiency of the stopping process (indicated by shorter SSRT) until young adulthood, both for global and selective stopping (Tillman et al., 2007; van de Laar et al., 2011; Williams et al., 1999). We were interested in further testing whether the magnitude of the reduction in SSRT differs between global and selective implementations of stopping. Finally, we explored secondary task-related factors beyond strategy and SSRT that could predict age group membership, including those associated with attention-related processes and with other forms of inhibitory control such as premature responding (“waiting impulsivity”) or proactive stopping (Aron, 2011; Voon et al., 2014).

2 | METHOD

2.1 | Participants

Ninety-seven typically developing children aged 6–7 and 100 typically developing preadolescents aged 10–11 were recruited from regular local schools in Madrid (Spain), along with 117 young adults aged 18–20 from a local university (Universidad Autónoma de Madrid, UAM). Participants had normal or corrected-to-normal vision, and no history of psychiatric, neurological, or sensory impairment. None of them had repeated a grade, nor did they need any curricular or special educational adaptations. Written informed consent to participate in the study was obtained from parents (with the child giving assent) when the participant was underage, and from the participants themselves in the case of young adults. The study was conducted according to the guidelines of the Declaration of Helsinki, and was approved by the Research Ethics Committee of the UAM.

Forty-three participants were excluded from analyses due to one or several of the following reasons: the strategy adopted to complete the task could not be identified ($n = 43$; see details below), the probability of responding on the stop-signal trials (respond|signal) was higher than 0.75 or lower than 0.25 ($n = 5$) and/or there was a high probability of omissions (>30% of go and/or ignore trials; $n = 3$). The final sample therefore consisted of 271 participants: 83 children aged 6–7 years (mean age ± SD, 6.58 ± 0.5), 86 preadolescents aged 10–11 (10.13 ± 0.36), and 102 young adults aged 18–20 (18.94 ± 0.78). Gender distribution did not differ between groups (chi-squared test; $\chi^2 = 1.54$, df = 2, $p = 0.46$). Data from a subset of participants in this sample were included in two previous studies (Rincón-Pérez et al., 2020; Rincón-Pérez et al., 2021).

2.2 | Stimulus selective stopping task

Participants completed a single run of a stimulus selective stop-signal task composed of three different stimuli: go, stop, and ignore (Figure 2). The go stimulus was presented for 1500 ms and consisted of a white arrow on a black background pointing downwards. All task trials contained a go stimulus to which participants should press the spacebar on a keyboard with the index finger of their dominant hand as fast as possible. Trials where only the go stimulus appeared are called go trials, and represent 60% of the total trials. The go stimulus was followed by a red diamond (stop signal) appearing around the go stimulus after a variable delay (stop signal delay, SSD) on another 20% of the trials, called stop trials. In these, participants were asked to try to cancel their motor response as soon as the stop signal appeared. In the remaining 20% of the trials, called ignore or continue trials, the go stimulus was followed by a green square (ignore signal) that likewise appeared around the go stimulus after a variable delay (ignore signal delay, ISD). In these, participants were asked to press the spacebar even if they saw the green square, and thus complete their already initiated motor response triggered by the go stimulus. We used bright colours because salient and easily detectable signals, such as the ones we employed here, minimize the influence of perceptual discrimination processes on the SSRT and the probability that differences between groups can be attributed to them (Verbruggen et al., 2019). Salient signals also facilitate the adoption of selective stopping strategies as opposed to a global non-selective strategy (Sánchez-Carmona et al., 2021) and might also minimize the probability of “trigger failures” on stop and ignore trials

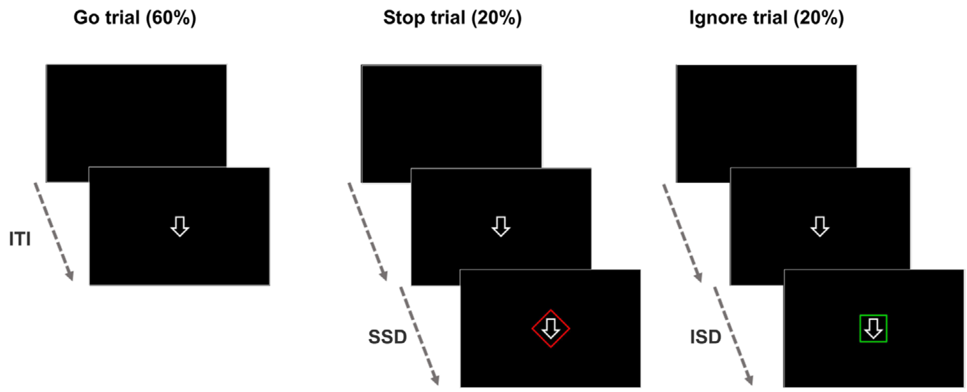

FIGURE 2 Schematic illustration of the stimulus selective stopping task used in this study. ITI = inter-trial interval; SSD = stop-signal delay; ISD = ignore signal delay

(Verbruggen et al., 2019). Overall, the task consisted of 230 trials (138 go, 46 stop, and 46 ignore) that lasted approximately 8.6 min. The order of trials was fully randomized.

Each trial began with a black screen devoid of any stimuli presented for either 500 or 1000 ms with equal probability (the inter-trial interval, ITI). Then the go stimulus was presented in all trials for 1500 ms. Thus, the total trial duration was either 2000 or 2500 ms. After the appearance of the go stimulus (and while it was still on-screen), the stop signal was presented after the SSD on 20% of the trials. SSD was initially set to 250 ms and then was adjusted dynamically from one stop trial to the next with a staircase tracking procedure based on each participant's performance. Specifically, in order to achieve approximately 50% probability of failed (and successful) stops per individual, the SSD increased by 50 ms in the next stop trial after a successful stopping and decreased by 50 ms in the next stop trial after a failed stopping. In ignore trials, the ignore signal was presented after the ISD, which was initially fixed to 250 ms but was always equated to the most recent SSD with no adaptive adjustment.

Instructions were given to participants before the task began, both verbally and displayed on the computer screen. We insisted on the need to respond as quickly as possible to the go stimulus and not wait for the ignore (green square) and the stop (red diamond) signals to appear. These instructions have been recommended so that participants do not try to strategically wait for signals to occur, which could interfere with the tracking procedure of the SSD and might prevent a reliable estimation of the SSRT (Verbruggen et al., 2019). Before the task, participants performed a first practice block of 20 trials with only go stimuli (i.e., without stop or ignore signals) to highlight the relevance of the go component of the stop-signal task (Verbruggen et al., 2019), and then a second practice block of 30 trials with the same characteristics described above to ensure understanding of the stimulus selective stopping task. It was designed and implemented in MATLAB using Psychtoolbox (www.psychtoolbox.org) from the script called STOP-IT generated by Verbruggen et al. (2008).

2.3 | Task performance

2.3.1 | Main task variables

Stopping strategies

We were firstly interested in identifying the strategies used by participants for solving the stimulus selective stopping task. Each individual's strategy was calculated by comparing their mean go RT with ignore RT and with failed stop RT through two independent *t* tests (Figure 1). To do this, we employed the method introduced by Bissett and Logan (2014), which has been previously applied in the study of the neural, genetic and behavioral correlates of stimulus selective stopping (Bissett & Logan, 2014; Rincón-Pérez et al., 2020; Sánchez-Carmona et al., 2016; Sánchez-Carmona et al., 2019; Sebastian et al., 2017). These comparisons result in three different possible strategies (two selective and one global, non-selective): *iDtS*, *dDtS*, and *StD*. The response is selectively inhibited in both the *iDtS* and *dDtS*, whereas it is globally inhibited in the *StD*. Bayes factor (BF) was employed to compare the evidence for and against the null hypothesis without bias (Rouder et al., 2009). A BF of one indicates that there is no difference between RTs, and a BF≠1 means that there is a difference. We used Rouder's Bayes factor calculator on the Perception and Cognition Lab website (http://pcl.missouri.edu/bf-two-sample) to convert *t* values and sample sizes into BFs. The Jeffrey-Zellner-Slow Prior with the default value of 1 was employed, which is recommended when there are no strong prior assumptions (Rouder et al., 2009).

SSRT

We were also interested in estimating the time required for participants to cancel their response once the stop signal is presented. SSRTs were computed using the integration method with replacement of go omissions because this approach is less susceptible to distortion from strategic slowing and skew in the go RT distribution than the mean method (Verbruggen et al., 2013; 2019). Importantly, the SSRT was calculated for each participant taking into account the strategy that was used. As mentioned in the introduction, the stopping and the responding processes are theoretically independent according to the horse race model (Logan et al., 1984), which holds true in the *StD* and the *iDtS* strategies. In those cases we used the integration method to calculate the SSRT based on the underlying go RT distribution. However, there is a dependence between responding and discriminating stop and ignore signals in the *dDtS* that violates the context independence assumption, and here the SSRT cannot be estimated reliably using the go RT distribution (Bissett et al., 2021; Bissett & Logan, 2014). These authors also proposed that if responding slows equally on both stop and ignore trials, the SSRT could be estimated through the integration method based on the ignore RT distribution. This is what we did for this strategy (*dDtS*), but it is worth noting that this solution is only valid as long as the assumption of equal slowing holds. Therefore, the SSRTs computed using the ignore RT distribution should be interpreted with caution.

2.3.2 | Secondary task measures

Premature responses

Those responses emitted at any point in the ITI before the onset of the go stimulus on a go trial. Importantly, we discounted those responses considered as atypically slow: if there was a response before the go stimulus but at the same time, no response was emitted in the previous trial, we considered this sequence as a slow response to the previous trial instead of a premature response to the current trial.

Post-signal behavioral adjustments

We compared the RT of go trials that occurred either after a failed stop trial (post-stop error) or after a correct ignore trial (post-correct ignore), with the RT of go trials that happened after a correct go trial (this "go-post-go" trial being the nearest one that precedes the error). This method prevents confounds derived from participants' changes in ability, motivation, or response caution throughout the task (Dutilh et al., 2012).

Intra-individual variability

A participant's variability in RT across trials within the task. It was estimated by fitting the participants' RTs to an ex-Gaussian distribution, which is formed by the convolution of a normal and an exponential distribution with three parameters: the mean and the standard deviation of the normal component (mu and sigma, respectively) and the mean and the standard deviation of the exponential component (both described by tau). Since mu is merely a reflection of average speed, the intra-individual variability is characterized particularly by sigma and tau. Sigma reflects the variability in fast (normal) responses of the distribution, and tau reflects variability in the extreme slow responses of the distribution (van Belle et al., 2015). Of note, the ex-Gaussian distribution was not fitted to the complete go RT distribution, because stop-go and ignore-go trial sequences would introduce proactive/post-signal adjustments that could bias response variability. Therefore, for this analysis we used only those go trials that followed another go trial (go-post-go). This fitting process was analyzed in the DISTRIB toolbox for MATLAB (Lacouture & Cousineau, 2008).

Go and ignore omissions

A go omission is a go trial without a response, while an ignore omission is an ignore trial without a response.

Go RT slope

We computed the slope of the linear least squares fitting model with respect to a subset of go RTs. Concretely, we selected only those go trials that followed another go trial (go-post-go), thus trying to avoid the speed adjustments that probably occur after stop and ignore signals. A slope value close to zero would suggest the maintenance of speed throughout the task. However, the more different to zero, the more it would suggest a speed increase (negative slope value) or a speed decrease (positive slope value), indexing the participant's ability to sustain attention throughout the task.

Proactive stopping

Following Verbruggen et al. (2019) we included a practice block without stop and ignore signals, with two goals: i) to emphasize the importance of the go task component to discourage waiting and ii) to obtain a measure of proactive stopping. Since task instructions state that the stop signal may occur at any time, participants inevitably anticipate having to stop at each trial. Consequently, go trials, influenced by the awareness of the presence of a stop signal, would show a proactive lengthening of RTs (Wessel, 2018). We can measure this proactive inhibition for each participant by taking the difference between go trials included in the stimulus selective stop-signal task and go trials included in the practice block. Mean RT of go trials during the task was computed by selecting only go-post-go trials.

2.4 | Data analysis

Contingency tables were employed to examine potential differences in the use of different strategies to perform the task among the three developmental age groups (children, preadolescents, and young adults). Since we expected certain strategies to be chosen by fewer participants, the Freeman-Halton extension of Fisher's exact test was used instead of a chi-squared test (Freeman & Halton, 1951). Cramer's *V* was reported as a measure of effect size. Follow-up Z-tests for independent proportions with Bonferroni correction for multiple comparisons were performed to detect significant differences among groups. SSRTs were then submitted to a 3 × 3 ANOVA with age group (children, preadolescents, adults) and strategy (*StD*, *iDtS*, *dDtS*) as between-subjects factors in order to assess differences between developmental age groups and a potential interaction between strategy and age group. Of note, the SSRT was estimated as a function of the strategy used by each participant, as previously described. Significant main effects and interactions were further investigated using post-hoc *t* tests with Bonferroni correction for multiple comparisons. Effect sizes were

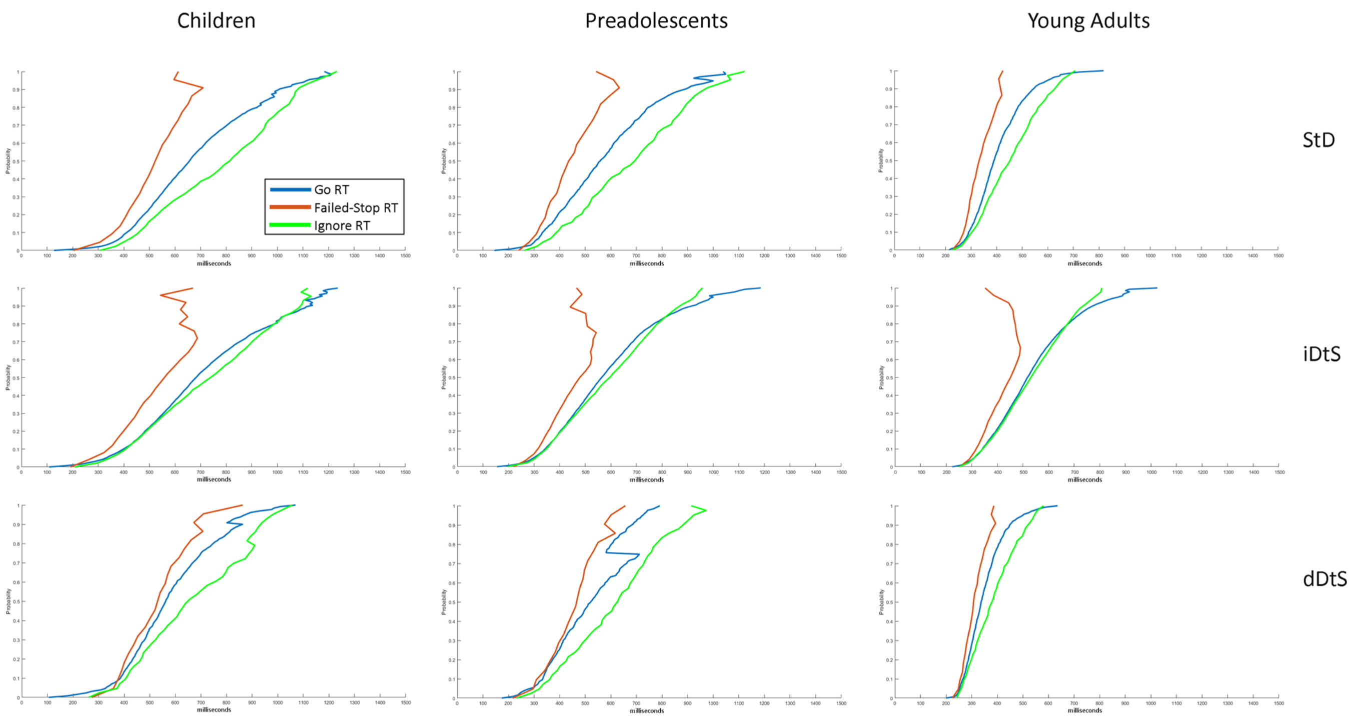

FIGURE 3 Cumulative distribution functions of response time (RT) for go, failed stop, and ignore trials for each age group (children, preadolescents, and young adults) and strategy (*StD*, Stop then Discriminate; *iDtS*, independent Discriminate then Stop; *dDtS*, dependent Discriminate then Stop)

measured using partial eta-square (η^2_p) for F values and Cohen's *d* for *t* values. Additionally, two multinomial regression analyses were performed to identify those factors predicting age group membership. The first regression included the two theoretical predictors on which this study focused (i.e., the strategy and the SSRT), whereas the second one was an exploratory, data-driven forward stepwise multinomial regression that included as potential predictors the secondary task measures described above in addition to strategy and SSRT (see Supplementary Material S1 for further details). Analyses were conducted with SPSS 26 unless mentioned otherwise. All reported p-values are two-tailed. Prior to statistical testing, data were examined for outliers. For each task measure and each age group, outliers were defined as those data points further than 1.5 times from the upper or the lower limit of the interquartile range. They were then replaced by the mean ± 2 standard deviations of the corresponding group. The number of outliers only represented 0.006% (17/2710) of the data set.

3 | RESULTS

We first identified the strategy used to perform the stimulus selective stopping task by comparing, for each participant individually, correct go, failed stop and correct ignore RTs (Figure 1), following the method proposed by Bissett and Logan (2014). Overall, we found that 52 participants used the global, non-selective stopping strategy (*StD*), whereas 219 adopted selective stopping strategies (199 *iDtS* and 20 *dDtS*). The strategy could not be classified in 43 participants (14 children, 14 preadolescents, and 15 young adults; 13.7% of the total sample). As described in the Section 2, these participants were excluded from further analysis. The cumulative distributions functions of RT for correct go, failed-stop and ignore trials for each group and strategy are presented in Figure 3. Moreover, means and standard deviations of go, failed-stop and ignore RTs, as well as of other variables of the task including SSD, SSRT, and the probability of responding on stop-signal trials, for each group and strategy separately can be found in Table 1, as recommended by consensus guidelines on the use of stop-signal tasks (Verbruggen et al., 2019).

Contingency tables were then made to examine potential differences in the use of strategies to perform the stimulus selective stopping task among children, preadolescents, and young adults. Specifically, we examined whether the proportion of adoption of each strategy differed among the three groups. A significant association between strategy and age group was found (Fisher's exact test = 18.85, $p = 0.001$, Cramer's $V = 0.19$; Figure 4). Z-tests for independent proportions revealed that the proportion of participants using the *StD* strategy was significantly greater in children (34.9%, $n = 29$) than in preadolescents (11.6%, $n = 10$) and young adults (12.7%, $n = 13$). No differences in its use were found between preadolescents and adults. By contrast, the proportion of participants using the *iDtS* strategy was significantly lower in children (56.6%, $n = 47$) than in preadolescents (81.4%, $n = 70$) and young adults (80.4%, $n = 82$). Again, no differences were observed between preadolescents and young adults in the adoption of this selective strategy. The three age groups did not differ significantly in the use of the *dDtS* strategy (children: 8.4%, $n = 7$, preadolescents: 7%, $n = 6$; young adults: 6.9%, $n = 7$).

TABLE 1 Means and standard deviations of go, failed stop and ignore RTs (variables used for identifying the strategy at the individual level), as well as of SSRT and secondary task measures, for each group and strategy separately

Variable	Age group																	
	Children (6–7 years)						Preadolescents (10–11 years)						Young adults (18–20 years)					
	Strategy						Strategy						Strategy					
	StD		*iDtS*		*dDtS*		*StD*		*iDtS*		*dDtS*		*StD*		*iDtS*		*dDtS*	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Go RT	680.57	113.92	697.25	138.53	611.06	73.56	584.94	128.79	585.46	135.02	529.44	135.70	408.27	33.64	538.37	154.54	350.29	47.89
Failed stop RT	520.18	104.81	526.38	99.42	571.34	85.39	461.09	100.68	444.48	92.78	489.58	118.98	345.60	29.86	425.09	116.14	329.84	37.81
Ignore RT	788.19	128.47	730.85	149.44	690.11	107.49	686.57	154.61	603.94	138.04	635.77	173.44	463.74	41.57	542.60	145.30	392.58	55.02
Probability of responding on stop-signal trials	0.48	0.05	0.49	0.08	0.51	0.04	0.51	0.03	0.51	0.07	0.50	0.06	0.51	0.04	0.48	0.06	0.54	0.05
SSD	290.28	112.39	301.60	109.27	235.71	59.26	252.50	97.50	252.86	116.53	220.83	92.76	153.07	38.16	255.17	141.09	85.25	42.98
SSRT	318.85	84.78	358.73	82.29	439.41	134.01	286.72	52.52	292.68	56.66	419.72	97.61	238.46	28.39	250.23	36.76	306.47	42.40
Premature responses	12.93	12.98	20.93	15.43	15.14	9.25	7.70	7.35	5.63	5.15	9.25	7.72	1.00	1.00	1.39	1.85	1.14	1.68
Post-stop error	144.95	153.25	99.50	135.23	108.54	144.78	25.65	103.51	107.46	111.67	138.93	160.83	75.69	54.72	68.66	85.33	19.29	27.67
Post-correct ignore	141.61	82.25	140.47	105.52	92.93	75.51	66.51	57.00	110.64	89.86	99.34	108.38	42.84	58.28	72.02	69.39	52.98	36.85
Sigma	139.34	66.50	170.98	70.61	118.85	65.47	111.01	78.12	117.67	74.48	70.56	45.72	48.90	14.68	97.24	75.56	30.89	20.91
Tau	157.31	74.71	161.71	93.65	116.06	74.42	170.84	87.23	145.33	70.21	140.88	114.14	72.84	45.39	102.55	70.98	57.74	40.72
Go omissions	5.45	5.28	7.11	5.71	4.43	3.69	2.80	3.01	2.37	2.91	2.71	4.19	0.15	0.55	1.13	1.31	0.14	0.38
Ignore omissions	1.10	1.92	1.74	1.70	1.29	1.38	0.50	0.71	0.50	0.78	0.50	0.84	0.15	0.38	0.13	0.38	0.00	0.00

Note: the SSRT was calculated using the go RT distribution in the *StD* and *iDtS* strategies, and using the ignore RT distribution in the *dDtS* strategy. Error data are given as a total number, not as a rate.
Abbreviations: *dDtS*, dependent discriminate then stop strategy; *iDtS*, independent discriminate the stop strategy; RT, reaction time; SD, standard deviation; SSD, stop-signal delay; SSRT, stop-signal reaction time; *StD*, stop then discriminate strategy.

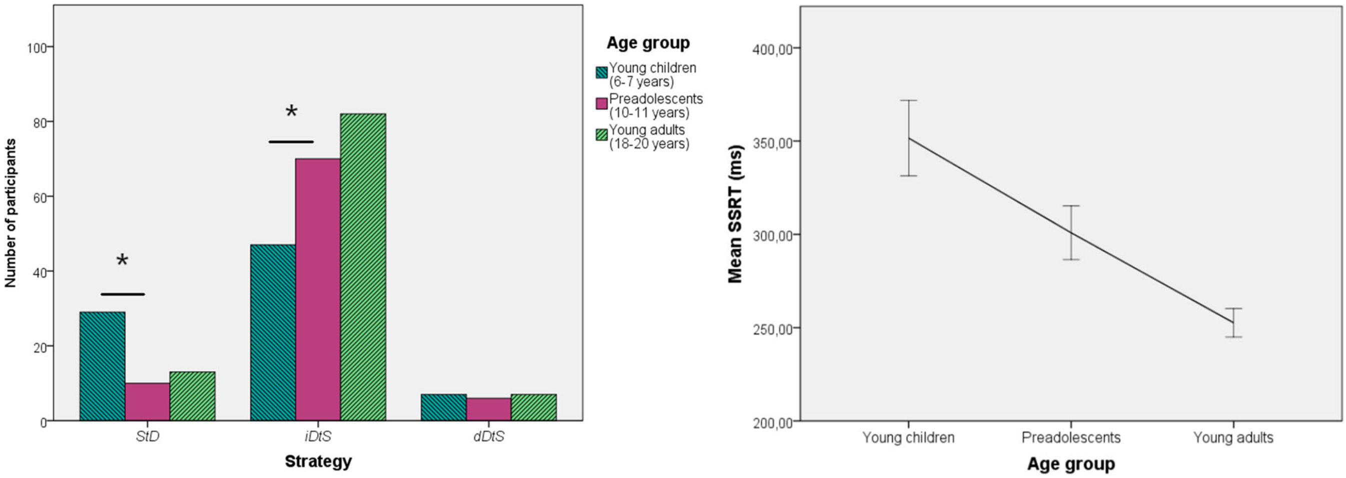

FIGURE 4 Differences in strategy use (left) and SSRT (right) by age group. * = significant differences. Error bars: 95% Confidence Interval

To assess differences between age groups and a potential interaction between strategy and age group in SSRTs, we conducted a 3 × 3 ANOVA with age group (children, preadolescents, adults) and strategy (*StD*, *iDtS*, *dDtS*) as between-subjects factors. The main effects of both age group (F(2,262) = 30.47, $p < 0.001$, $\eta^2_p = 0.19$) and strategy (F(2, 262) = 20.85, $p < 0.001$, $\eta^2_p = 0.14$) were significant. Post-hoc t-tests with Bonferroni correction indicated greater SSRT for children compared with preadolescents ($p < 0.001$; Cohen's $d = 0.63$) and young adults ($p < 0.001$; Cohen's $d = 1.44$), as well as preadolescents versus young adults ($p < 0.001$; Cohen's $d = 0.89$) as seen in Figure 4, irrespective of the strategy adopted. With respect to the main effect of strategy, post hoc *t* test with Bonferroni correction revealed greater SSRT for *dDtS* compared with *iDtS* ($p < 0.001$; Cohen's $d = 1.28$) and *StD* ($p < 0.001$; Cohen's $d = 1.08$), irrespective of age group. Although SSRT was numerically faster in the *StD* than in the *iDtS* in all age groups as expected (see Table 1), differences between these two strategies were not significant ($p = 0.87$, Cohen's $d = 0.03$). The interaction of age group and strategy was not significant (F(4,262) = 1.49, $p = 0.2$): there was a reduction of the SSRT with age in all strategies (lower SSRT values in the older age groups). However, it should be noted that further post-hoc ANOVAs conducted for each strategy separately revealed a larger effect size for SSRT differences between groups in the *dDtS* (difference of 132.94 ms between young adults and children, F(2,17) = 3.63, $p < 0.05$, $\eta^2_p = 0.29$) and the *iDtS* strategy (difference of 108.50 ms between young adults and children, F(2,196) = 53.71, $p < 0.001$, $\eta^2_p = 0.35$), compared to the *StD* strategy (difference of 80.38 ms between young adults and children, F(2,49) = 6.07, $p < 0.05$, $\eta^2_p = 0.19$).

These results were further confirmed and extended by a theoretically guided multinomial logistic regression (Supplementary Material S1). Specifically, we found that both strategy and SSRT predicted age group membership: participants adopting a selective strategy or participants with shorter SSRT were more likely to belong to the older age groups. However, while strategy discriminated between children and preadolescents (but not between preadolescents and adults), the SSRT was a predictor of membership across all age groups. We then carried out an exploratory, data-driven multinomial logistic regression with age group as the dependent variable to identify potential predictors of age group membership. Besides the SSRT and strategy, we found three variables that predicted age group membership: premature responses, post-ignore slowing and ignore omissions. Both premature responses and post-ignore slowing differentiated between the three age groups, whereas ignore omissions discriminated between children and preadolescents (and between children and young adults). A detailed description of these results can be found in Supplementary Material S1.

3.1 | Control analyses

To further confirm the validity of our adaptive-algorithm and to rule out the possibility that the experimental effects were related to between-group differences in stopping failures (which generate emotional frustration and error monitoring; Li et al., 2006; Sánchez-Carmona et al., 2016), we conducted an ANOVA on the probability of responding on stop-signal trials [p(respond|signal)]. As expected, stopping failures did not differ between age groups (F(2, 262) = 0.58, $p = 0.56$) or in the interaction between age group and strategy (F(4, 262) = 1.38, $p = 0.24$).

Secondly, for each participant and each SSD we compared failed stop RTs to go RTs from the immediately preceding trial following the method recently proposed by Bissett et al. (2021). This allows us to further assess violations of go context independence in our data. Supplementary Material S2 reports details of analyses and results. Briefly, we observed violations of context independence in the *dDtS* strategy, whereas no violations were observed in the *StD and iDtS* strategies at any SSD.

4 | DISCUSSION

In this cross-sectional study we investigated the qualitative and quantitative developmental changes in selective stopping in over 300 participants, from children aged 6–7 to young adults aged 18–20. At the qualitative level, we observed age-related changes in the proportion of the strategies used by participants to perform the stimulus selective stop-signal task. Specifically, we found an increase in the use of the independent selective stopping strategy (*iDtS)* and a decrease in the use of the global, non-selective stopping strategy (*StD*) in preadolescents relative to younger children, with no differences between preadolescents and young adults. These findings suggest that preadolescence may be the endpoint of the maturation of processes needed to achieve task requirements underlying stopping selectively, in line with previous studies (Rincón-Pérez et al., 2021).

The question of when do children begin to adopt selective strategies in this task needs to be addressed in future studies with wider age ranges. Present results suggest that children at the beginning of middle childhood are already able to stop selectively at least to an extent, even if the ability is not completely mature. Therefore, the question of when selective stopping begins to develop remains unanswered. Although there are no prior data on the early development of selective stopping, inhibition in general seems to develop from early childhood to young adulthood (Best & Miller, 2010; Cope et al., 2020). Some basic forms of inhibitory control are present as early as the first year of life (Holmboe et al., 2018), followed by a rapid development throughout the preschool years (Garon et al., 2008; Wiebe et al., 2012). In this light, the earliest appearance of selective inhibitory abilities is yet to be identified. Likewise, a deeper investigation regarding whether the use of these strategies remains stable all across the lifespan (including aging) is also needed to complete the picture. While there is evidence from a cross-sectional study pointing to a lack of differences between younger and older adults (Hsieh & Lin, 2017), the full developmental trajectory of selective stopping strategies should be confirmed by the findings of longitudinal studies.

The dependent selective stopping strategy (*dDtS)* was adopted by a similarly low number of participants across all age groups. This finding was expected because we used perceptually salient signals and a simple go task (i.e., one go stimulus mapped onto one response), two experimental conditions that seem to facilitate the adoption of a selective stopping strategy that complies with the context independence assumption (i.e., the *iDtS*). Indeed, recent evidence shows that individuals preferentially adopt the *iDtS* strategy when perceptual discrimination between signals is easy, whereas the use of the *dDtS* and the *StD* increases when signal discrimination is difficult (Sánchez-Carmona et al., 2021). Likewise, indirect evidence suggests that the *iDtS* is preferentially adopted when participants perform a simple go task (e.g., present results and Sánchez-Carmona et al., 2021), whereas the *dDtS* is mostly used when participants perform a choice go task (i.e., two different go stimuli mapped onto two different responses; Bissett & Logan, 2014; Sánchez-Carmona et al., 2016, 2019). Overall, these findings can be interpreted within the framework of the dual-task interference hypothesis: go discrimination and stop/ignore signal discrimination may rely on the same processing bottleneck (Pashler, 1994), as proposed by Bissett and Logan (2014). Discriminating stimuli in a choice go task and discriminating stop and ignore signals that are perceptually similar increases processing demands and slows go and ignore RTs, which might lead to a violation of go context independence. Therefore, a tentative recommendation for future selective stopping studies would be to use a simple go task and salient signals to favor the use of a selective stopping strategy that preserves the independence between going and stopping and allows a valid estimation of the main variables of the task.

Importantly, Bissett et al. (2021) have recently reported that violations of the context independence assumption may be widespread in stopping research, particularly in selective stopping studies. Until now, context independence has been typically assessed by comparing mean go RT and mean stop failure RT across all SSDs. However, this method is conservative and overlooks severe violations of independence, which have been mainly observed at short SSDs. Reanalyzing previously published selective stopping data, Bissett et al. (2021) found that for short SSDs, participants categorized as *StD* and *dDtS* showed failed stop RTs longer than go RTs (thus violating the independence assumption), but when SSDs were long both strategies showed failed stop RTs shorter than go RTs (the independence assumption was met). These results question prior procedures for categorizing subjects by individual differences in strategies (e.g., Bissett & Logan, 2014; Rincón-Pérez et al., 2021; Sánchez-Carmona et al., 2016; Sebastian et al., 2017), which assume that there are violations of independence at all SSDs in *dDtS*, and no violations of context independence in *StD* at any SSDs. In this light, differences in strategies might be an artefact of different individuals sampling different SSD distributions. Remarkably, our supplementary analyses following the new method by Bissett and colleagues did not indicate context independence violations in any of the SSD in the *StD* and *iDtS* strategies (Supplementary Material S2). By contrast, violations were observed in the *dDtS*. Thus, current results fit the original proposal made by Bissett and Logan (2014) to categorize individuals into different strategies. The use of a simple go task in conjunction with perceptually salient signals could again explain the lack of context independence violations in the *StD* and *iDtS* strategies, in contrast to other selective stopping datasets (Bissett et al., 2021).

At the quantitative level, we investigated developmental changes in the SSRT across strategies. We found that the SSRT decreased from the youngest (children) to the oldest age group (young adults), irrespective of the strategy used. Therefore, the developmental trajectory of the SSRT seems to be similar regardless of which stopping strategy is used. The efficiency gain of the stopping process with age is in accordance with our hypotheses, as well as with previous studies that used both global (Fosco et al., 2019; Urben et al., 2011; van de Laar et al., 2011) and selective tasks without controlling for strategy (Bedard et al., 2002; Kray et al., 2009; van de Laar et al., 2011). Our results are also in accordance with previous studies that point to a development of general inhibitory skills during middle childhood and adolescence (Best & Miller, 2010; Brocki & Bohlin, 2004; Howard et al., 2014; Humphrey & Dumontheil, 2016; Vara et al., 2014). However, it should be noted that the magnitude of SSRT reduction in young adults relative to children was greater in selective strategies compared to the global strategy. Thus, it could be hypothesized that global stopping might start developing earlier than selective stopping so that by middle childhood and adolescence the gain in efficiency is less pronounced than for selective stopping. Nonetheless, even if the ability to adopt a selective strategy is mature at the preadolescent period, the speed of stopping continues to mature throughout adolescence until young adulthood both for global and selective stopping.

Additionally, the main effect of strategy on the SSRT was significant: participants using the *dDtS* strategy had larger SSRTs relative to those adopting the *StD* and *iDtS* strategies. Thus, we found no significant differences in the length of the SSRT between the global, non-selective strategy (*StD*) and the independent selective strategy (*iDtS*), irrespective of age group. This finding seems at odds with the notion that the SSRT in the *iDtS* should be longer than in the *StD* because only the former includes the time taken to discriminate between stimuli. However, although this comparison did not reach statistical significance, the SSRT in the *iDtS* strategy was numerically slower than in the *StD* strategy across all age groups (e.g., up to even 40 ms in the children group), as is theoretically expected. By contrast, the SSRT in the *dDtS* strategy was longer than for the other two strategies, which would suggest that the SSRT is elongated only when there is a dependence between responding and discriminating stop and ignore signals (Verbruggen & Logan, 2015). Of note, severe independence violations occurred in individuals using this strategy (see Supplementary Material S2). The estimation of the SSRT in the *dDtS* strategy using the ignore RT distribution (rather than using the traditional go RT distribution) as we did here still lacks validation (Bissett & Logan, 2014), so these findings warrant further confirmation from additional studies.

The observed qualitative and quantitative age-related changes were confirmed and extended by multinomial logistic regressions (Supplementary Material S1). Indeed, both the theoretical-driven and data-driven multinomial logistic regressions highlight the key role of strategy and SSRT as relevant predictors of developmental status (the former only discriminated between children and preadolescents, whereas the latter discriminated across all age groups). Moreover, besides the SSRT and strategy we observed that some task-related measures associated with inhibitory control processes (premature responses and post-ignore slowing) and attentional processes (ignore omissions) predicted age group membership. These secondary measures can be therefore considered as relevant predictors of age group status in future developmental studies using selective stopping tasks.

Both premature responding and post-ignore slowing discriminated between all age groups. The former is a measure of "waiting impulsivity," which is the inability to wait to emit responses until the stimulus appears (Dalley & Robbins, 2017; Voon et al., 2014). Waiting impulsivity is distinct but related to the stopping impulsivity measured by the SSRT (see Robbins & Dalley, 2017; Voon, 2014). Developmental studies on premature responding are scarce, but their results suggest that it correlates negatively with age in children and adolescents (Rubia et al., 2007). In this line, we showed here that participants making less premature responses were more likely to be either in the young adult group, or in the preadolescent compared to the child group. These results suggest a similar developmental trajectory for these two types of impulsivity/inhibitory control, although further studies are needed to substantiate this conclusion.

Post-ignore slowing is the motor slowing after a successful ignore trial, and can be conceptualized as a measure of cognitive control. The stimulus selective stopping task allows to examine behavioral adjustments to two different types of rare events (stop and ignore) that are associated, however, with an erroneous (unsuccessful stop trials) or with a correct outcome (successful ignore and successful stop trials). Here we found equal slowing after failed stop and correct ignore trials across groups and strategies, and an absence of slowing following successful stop trials (see Supplementary Material S3). These findings are difficult to reconcile with a single hypothesis for post-signal adjustment such as the error detection, the response conflict, the goal priority or the surprise hypothesis (for a review see Bissett & Logan, 2011; Wessel & Aron, 2017). Indeed, it is possible that overlapping but also distinct mechanisms might contribute to post-ignore and post-stop slowing. It can be speculated that emitting a response after a signal appears generates a high level of conflict and the activation of processes aimed at monitoring the outcome of the action, which would produce slowing both after correct ignore trials (to confirm that the emitted response was adequate to task demands) and failed stop trials (to prevent further inhibitory errors). Even if task instructions assign the same importance to stopping and going, participants seem to favor stopping as the perceived main goal of the task. Therefore, emitting a response after stop and ignore signals would generate a high level of conflict, while successful response inhibition to stop signals would elicit less conflict since it aligns with the perceived objective of the task. Further studies are needed to elucidate the exact cognitive processes underlying post-ignore and post-stop slowing (as well as their potential relation to strategies). With respect to development, prior studies focusing on behavioral adjustments after failed stops have mainly reported a decrease in post-error slowing with age (Smulders et al., 2016), which is similar to what was observed here with post-ignore slowing. These results suggest that premature responding and post-ignore slowing could be interesting developmental markers of different forms of inhibitory control in future studies using selective stopping tasks.

Finally, the other significant predictor in the exploratory regression analysis was ignoring omissions, even if they did not discriminate between all age groups. This variable is related to attentional processes needed to perform the task. Weaker attentional-related abilities result in distractibility and attentional lapses, which can lead to more omission errors (Lin et al., 2014; Vaurio et al., 2009). In agreement with the view that middle childhood is critical for the improvement of attention-related functions (Betts et al., 2006; Klimkeit et al., 2004; Suades-González et al., 2017), we found that ignore omissions were more likely to be committed by children. An interesting question is why ignore omissions are a significant predictor of age group, but go omissions are not. A go omission implies ignoring only the go stimulus, while an ignore omission involves disregarding both the ignore signal and the go stimulus in the same trial. Thus, ignore omissions could be a sign of greater distractibility than go omissions.

In conclusion, by characterizing the qualitative and quantitative changes between the three age groups performing a stimulus selective stopping task, this study provides new insights into the development of selective stopping. We found that the ability to stop a response selectively reaches its final point by early preadolescence, and remains stable afterwards at least until young adulthood. By contrast, the efficiency or speed of stopping (SSRT) continues to mature throughout adolescence until young adulthood, both for global and selective implementations of stopping. We also provide some preliminary findings regarding other task-related variables related to cognitive control and attentional processes involved in selective stopping that are of interest for future developmental studies using a selective stopping task. Moreover, present results may help to better understand the experimental conditions in which the context independence assumption of current models of stopping is preserved when using selective stopping tasks. Although current results need to be confirmed and extended in longitudinal studies, they provide new insights into the development of relevant aspects of inhibitory control.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

ETHICS STATEMENT

The study was conducted according to the guidelines of the Declaration of Helsinki, and was approved by the Research Ethics Committee of the UAM.

DATA AVAILABILITY STATEMENT

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

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