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Hot and cool response inhibition abilities develop linearly from late childhood to young adulthood

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HIGHLIGHTS

- Hot and cool response inhibition develop linearly from late childhood to young adulthood.
- Hot response inhibition development appears to be more protracted than cool one.
- Exerting response inhibition in an affectively charged context is more challenging.
- Hot response inhibition is less efficient than cool inhibition in adolescents.

ABSTRACT

Inhibitory control involves different types of inhibition processes, such as interference control and response inhibition. In an affectively neutral context, both inhibition processes develop linearly with age. In an affectively charged context, however, the development of these inhibition processes is still debated, and no study has investigated the development of the ability to inhibit an initiated motor response, such as in a stop signal task (SST), from late childhood to young adulthood. We asked children, adolescents and young adults to perform a cool or a hot version of the SST using neutral or emotional nonverbal vocalizations as stop signals. We showed that cool and hot response inhibition abilities develop linearly from late childhood to young adulthood. The development of this ability in an affectively charged context appears to be more protracted than in a neutral one. Exerting response inhibition in an affectively charged context is more challenging than in a neutral context especially during adolescence.

KEYWORDS: Response inhibition, Stop signal task, Cool, Hot, Development.

1. INTRODUCTION

As humans living in complex societies, we rely on a number of automatisms to efficiently navigate our physical and social environments. In some contexts, we need to resist such automatisms to avoid negative outcomes. For instance, during a pandemic crisis, such as the COVID-19 crisis, people need to resist automatic social behaviors (e.g., hugging, shaking hands, or kissing) and adopt new behaviors (e.g., physical distancing) to control the spread of the virus. Adopting such behaviors typically requires withholding a prepotent response in an affectively charged context. Resisting such automatisms as well as temptations, distractions or interferences and adapting to conflicting situations relies on inhibitory control (IC, Diamond, 2013; Diamond & Ling, 2016), which develops differently in affectively neutral and charged contexts from childhood to adulthood (e.g., Aïte et al., 2018; Tottenham, Hare, & Casey, 2011). In the present study, we investigated for the first time the development of the ability to inhibit an initiated motor response, such as when we refrain from hugging someone after we have started moving toward him/her, in an affectively neutral or charged context from late childhood to young adulthood.

IC is not a unitary construct but rather involves different types of inhibition processes, such as *interference control* and *response inhibition*, depending on the activity that needs to be inhibited (Eagle et al., 2008; Khng & Lee, 2014; Rubia et al., 2001; Scheres et al., 2004). *Interference control* is a set of processes that allows the selective attendance to task-relevant information by inhibiting task-irrelevant information (Diamond, 2013). For instance, in the Color-Word Stroop task (Stroop, 1935), in which participants must identify the ink colors of printed color words (e.g., BLUE written in red), individuals typically need to inhibit the color denoted by the word (i.e., blue, the task-irrelevant information) to identify the ink color of the printed word (i.e., red, the task-relevant information). *Response inhibition* is a set of processes that allows withholding a prepotent motor response in response to a stop signal. In the

Go/NoGo task, participants press a button in response to a given stimulus and have to refrain from doing so when a stop signal is presented simultaneously with (or instead of) the go signal (e.g., Donders, 1969). The Go/NoGo task typically assesses the ability to inhibit a reinforced motor response. In the stop signal task (SST), participants make simple decisions in response to the presentation of a stimulus but must withhold their motor response when a stop signal is presented with various delays after a go signal (Logan, 1994; Logan & Cowan, 1984). The SST assesses the ability to inhibit an initiated motor response. Importantly, these two types of *response inhibition* appear to be relatively independent of one another (Eagle et al., 2008; Rubia et al., 2001; Scheres et al., 2004).

In an affectively neutral context, there is a general consensus that *interference control* (Aïte et al., 2018) and *response inhibition* (Go/NoGo task: Hare et al., 2008; Schel & Crone, 2013; Somerville, Hare & Casey, 2011; Tottenham et al., 2011; SST: Bedard et al., 2002; Carver, Livesey, & Charles, 2001; Tillman, Thorell, Brocki, & Bohlin, 2007; Urban, Linden, & Barisnikov, 2012; Williams, Ponsse, Schachar, Logan, & Tannock, 1999) abilities develop linearly with age. In an affectively charged context, the development of *interference control* and *response inhibition* is still debated (see Schweizer, Gotlib, & Blakemore, 2020). Neurodevelopmental imbalance models of adolescence hypothesize an adolescent-specific developmental pattern of IC abilities in an affectively charged context due to an imbalance between a hyperactive emotional subcortical network and an immature prefrontal network during this period of life (Casey, 2015; Casey & Caudle, 2013). In agreement with this model, studies have reported quadratic developmental patterns for both *interference control* and *response inhibition* abilities. For instance, Aïte et al. (2018) revealed a quadratic effect of age on performance in an affectively charged version of the Stroop task, with adolescents displaying worse *interference control* abilities than children and adults. Similarly, some studies have reported a quadratic developmental pattern for *response inhibition* abilities in an

affectively charged Go/NoGo task associated with stronger ventral striatum activity in adolescents than in children and adults and a linear decrease in inferior frontal gyrus activity with age (Hare et al., 2008; Somerville et al., 2011). However, other studies have reported a linear developmental pattern for this ability using the same task with a protracted development of *response inhibition* in an affectively charged context (Schel & Crone, 2013; Tottenham et al., 2011). This finding is in line with another model of the development of executive functions in affectively neutral or charged contexts that assumes a later development of executive functions and of IC in particular in an affectively charged than in an affectively neutral context (Zelazo & Carlson, 2012). Regarding the ability to inhibit an initiated motor response in an affectively charged context, several studies on adults using the SST provided evidence that response inhibition was impaired (Herbert & Sütterlin, 2011; Kalanthroff, Cohen, & Henik, 2013; Kryptos, Jahfari, van Ast, Kindt, & Forstmann, 2011; Rebetz, Rochat, Billieux, Gay, & Van der Linden, 2015; Verbruggen & De Houwer, 2007), improved (Pessoa, Padmala, Kenzer, & Bauer, 2012) or was unaffected (Sagaspe, Schwartz, & Vuilleumier, 2011) in an affectively charged context. To date, only one study using the SST investigated the development of the ability to inhibit an initiated motor response in an affectively neutral or charged context (Urban et al., 2012). Urban et al. (2012) reported a linear development of both cool and hot response inhibition abilities from childhood (i.e., 6 years of age) to early adolescence (i.e., 13 years of age).

However, no study to date has investigated the development of the ability to inhibit an initiated motor response in an affectively charged context from late childhood to adolescence and young adulthood. To do so, we asked children (9 - 11 years old), adolescents (13 - 16 years old) and young adults (18 - 30 years old) to perform an affectively neutral (hereafter referred to as “cool”) and charged (hereafter referred to as “hot”) version of the SST. In the Go trials of the SST, participants were required to determine the left-right direction of an

arrow displayed on a screen by pressing one of two response buttons. In the Stop trials, an auditory stop signal was presented with variable delay after the presentation of the Go stimulus. Participants were instructed to withhold their response whenever they heard the stop signal. The stop signal consisted of an affectively neutral or charged nonverbal vocalization (Belin, Fillion-Bilodeau, & Gosselin, 2008). If the imbalance adolescence model (Casey, 2015; Casey & Caudle, 2013) is correct, then performance (i) should increase with age in the cool SST and (ii) be lower in the hot than the cool SST in adolescents but not in children and in adults. In addition, if the Zelazo's model (Zelazo & Carlson, 2012) is correct then (i) performance should increase with age in both the cool and hot SST and (ii) the performance should improve earlier in the cool than the hot SST.

2. METHODS

2.1. Participants

Eighty-two young adults (18 - 30 years old), 70 adolescents (13 - 16 years old) and 95 children (9 - 11 years old) were recruited from public universities and middle and elementary schools supporting diverse populations with a wide range of socioeconomic statuses. One adult participant, 6 adolescents and 3 children were discarded from the analyses due to technical issues during data collection (i.e., data were not fully recorded for those participants). An additional 10 participants (4 children, 1 adolescent and 5 adults) were discarded because their accuracy on the Stop trials (below 30% or above 70% of correct Stop trials) and 12 (3 children, 4 adolescents and 5 adults) because their SSRTs differ by more than 2 SD of the mean SSRTs of their age by type of SST groups. The proportion of participants discarded did not differ between the age by type of SST groups, $\chi^2(2) = .78$, $p = .67$. Therefore, the data analyses were restricted to 71 adults ($M = 20.83 \pm 1.75$ years old; 25 males), 59 adolescents ($M = 14.05 \pm 0.68$ years old; 25 males) and 85 children ($M = 9.85 \pm$

0.61 years old; 43 males). The proportions of males to females did not differ among the young adults, the adolescents and the children, $\chi^2(2) = 3.75, p = .15$. Participants were randomly assigned to the cool (38 adults, 26 adolescents and 47 children) or hot SST (33 adults, 33 adolescents and 38 children). Twenty-five participants were left-handed, 13 of which were assigned to the cool condition (8 children, 2 adolescents and 3 adults) and 12 to the hot condition (6 children, 4 adolescents and 2 adults). The proportion of left-handed participants did not differ between the age by type of SST groups, $\chi^2(2) = 1.11, p = .57$. Sample size was determined by running an a priori power analysis using G*Power 3.1.9.2 (Faul, Erdfelder, Buchner, & Lang, 2009), revealing that a minimum of 211 participants would be needed to detect a medium effect size of 0.25 (according to Cohen's effect size conventions) within a 2 (SST: cool vs. hot) x 3 (Age: children vs adolescent vs. young adult) between-subject analysis of variance (ANOVA) with power $(1 - \beta)$ set at .80 and α set at .05. All participants had normal or corrected-to-normal vision and were typically developing. All of the participants, or parents (legal guardians) for minors, gave written consent. All participants were also tested in accordance with the national and international norms that govern the use of human research participants.

2.2. Stimuli

Each participant performed either the cool or the hot SST. Both versions of the task were implemented with E-prime 2.0.10 (Psychology Software Tools, Pittsburgh, PA) and performed individually on a computer equipped with size-adjustable headphones through which an auditory signal could be presented. In both the cool and hot SST, participants were presented with arrows pointing to the right or to the left (i.e., Go stimulus) (see Figure 1).

In the present study, nonverbal vocalizations, adapted from the Montreal Affective Voices (MAV) database (see Belin et al., 2008), and consisting of interjections, using the vowel /a/,

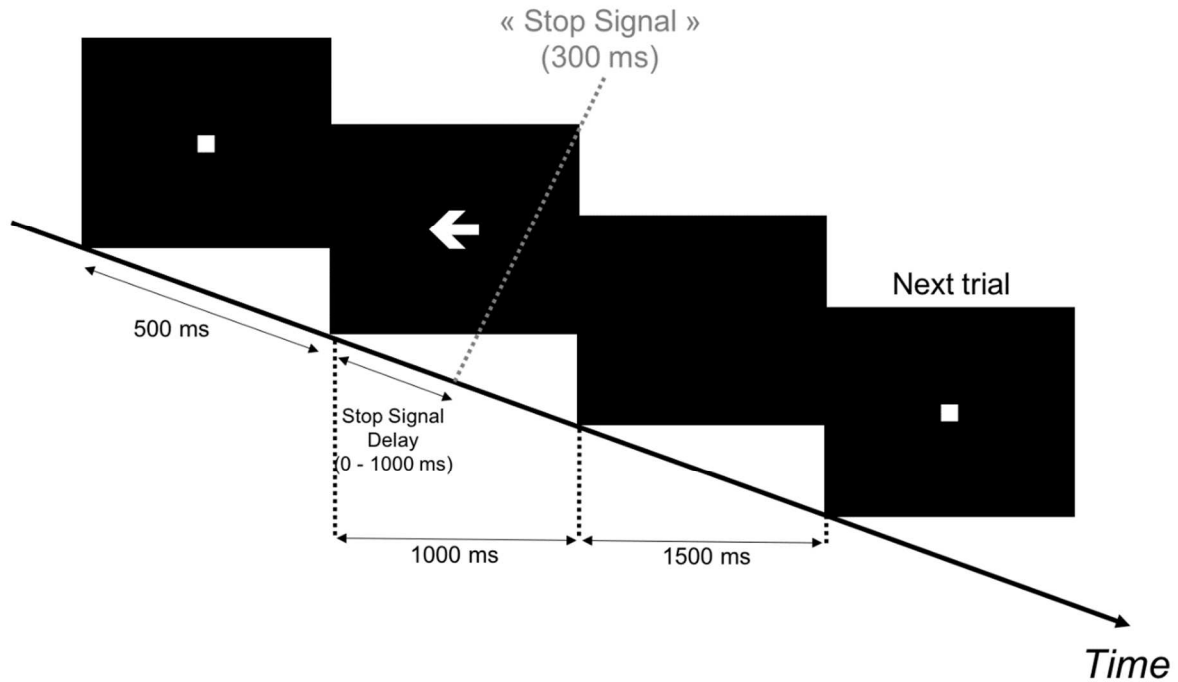
expressing neutral, fear (i.e., screams) and anger (i.e., expression of rage) expressions, were used as stop signals. Note that previous studies also used auditory cues (e.g., bip) as stop signal in both cool (e.g., Bedard et al., 2002; Carver et al., 2001; Logan & Cowan, 1984; Logan, Schachar, & Tannock, 1997; Williams et al., 1999) and hot (Herbert & Sütterlin, 2011; Kalanthroff et al., 2013; Kryptos et al., 2011; Rebetez et al., 2015) versions of the SST. Four neutral stop signals (i.e., two female and two male neutral nonverbal vocalizations) and four emotional stop signals (i.e., two female and two male nonverbal vocalizations conveying fear and anger) were thus used in the cool and hot version of the SST, respectively.

To meet the SST demands, all the non-verbal vocalizations from the MAV database (i.e., four neutral, two conveying fear and two conveying anger) were shortened to last 300 ms. A pre-test was thus conducted ahead on 21 young adults to enable to objectively shift our choice towards the neutral and emotional vocalizations reported above. Indeed, using a 1 (i.e., negative emotion) to 7 (i.e., positive emotion) Likert scale, participants rated the selected non-verbal vocalizations as followed: 3.95 (\pm 0.38) and 4.19 (\pm 0.40) for neutral female vocalizations; 3.95 (\pm 0.50) and 4.09 (\pm 0.62) for neutral male vocalizations; 1.38 (\pm 1.32) and 2.65 (\pm 1.31) for fear from female and male voices, respectively; and 1.90 (\pm 0.89) and 1.76 (\pm 0.99) for anger from female and male voices, respectively. Using one-sample t-tests, we confirmed that all the vocalizations conveying negative emotions scored significantly below 4 ($p < .001$ for all the four emotional vocalizations used in this SST paradigm) and neutral vocalizations did not scored differently from 4.

2.3. Procedure

In each Go trial, an arrow oriented either to the right or to the left was displayed on a screen. Participants were instructed to press, as quickly and accurately as possible, either the right or the left button of a computer mouse, respectively, using their right hand. In half of the

trials, the arrow was pointing to the right, and in the other half, to the left. Each Go trial began with the presentation of (i) a fixation stimulus (i.e., a white square) for 500 ms, followed by (ii) an arrow for 1000 ms, and (iii) a black screen for 1500 ms (see Figure 1). Participants could provide an answer up to 2000 ms after the presentation of the arrow. Stop trials were similar to Go trials, except that a brief sound of 300 ms (i.e., stop signal) was presented with a variable stop signal delay (SSD) after the presentation of the arrow (Figure 1). Participants were instructed to refrain from pressing either of the two response buttons when they heard the stop signal. The initial delay between the presentation of the arrow and the stop signal (i.e., the SSD) was set to 150 ms. This SSD was then dynamically adjusted throughout the experiment, i.e., if participants successfully inhibited their motor response on the previous Stop trial, the SSD was increased by 50 ms on the subsequent Stop trial (up to a maximum delay of 1000 ms), while if they failed to inhibit their response, the SSD was decreased by 50 ms on the subsequent Stop trial (down to a delay of 0 ms) (Logan et al., 1997). Using such a staircase procedure allows to maximize the probability of having participants successfully inhibiting their prepotent motor response on 50% of the Stop trials for each condition. Note that participants who deliberately engage in a strategy consisting in delaying their response could reach accuracy rate well above 50% on the Stop trials. Similarly, participants rushing to press the response buttons in all trials will reach accuracy rate well below 50%.



- Insert Figure 1 about here -

Figure 1: Go and Stop trials in the cool and hot SSTs.

The cool and hot SSTs included (i) a practice block of 16 trials, including both Go and Stop trials (i.e., 12 Go trials and 4 Stop trials), to allow the participants to become familiar with the task and (ii) two experimental blocks of 64 trials each (i.e., 48 Go trials and 16 Stop trials per block). In both experimental conditions, (i) the Go and Stop trials were pseudo-randomly presented, and (ii) each of the four vocalizations (i.e., 4 neutral vocalizations - in the cool SST - or 4 vocalizations conveying either fear or anger - in the hot SST) was randomly presented 8 times.

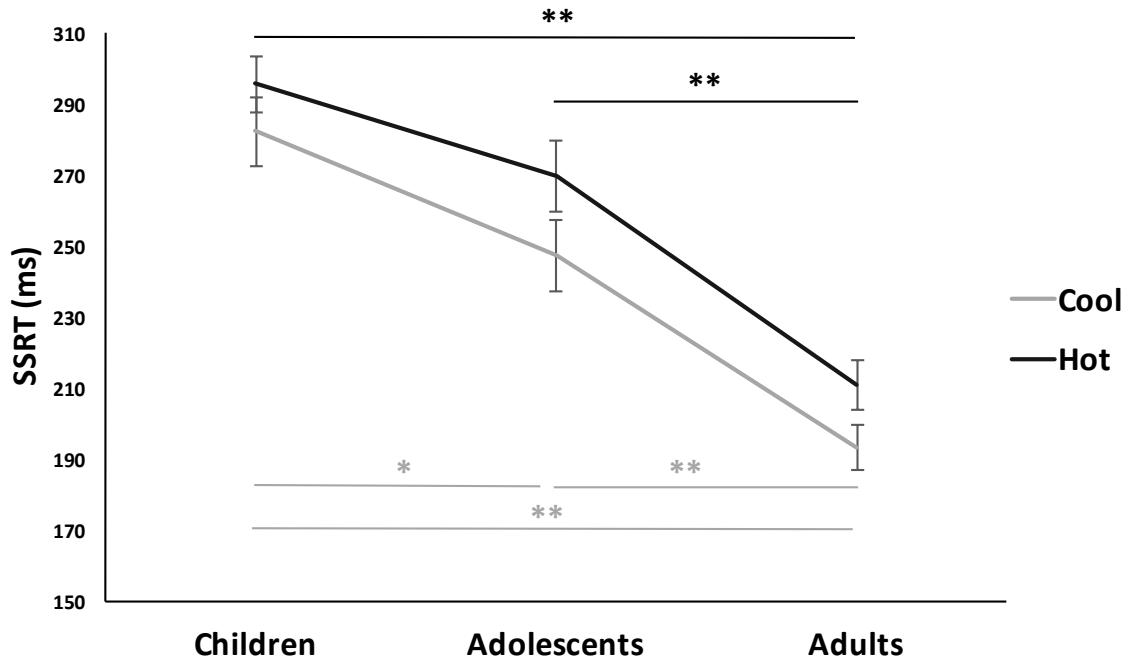
2.4. Statistical analyses

For the cool and hot SSTs, we computed a stop signal reaction time (SSRT) by subtracting the average SSD from the median reaction time on correctly performed Go trials (Aron & Poldrack, 2006; Logan & Cowan, 1984). Longer SSRTs revealed lower IC efficiency. To

investigate the developmental pattern of the ability to withhold an initiated motor response in an affectively neutral or charged context, we ran a 3 (Age: children, adolescents and young adults) x 2 (i.e., SST: cool vs. hot) between-subjects ANOVA on the SSRTs. For this analysis, we reported the effect size in terms of the amount of variance accounted for by the independent variables (partial eta-squared, η^2_p). Assuming that the mean SSD of the second block may be more sensitive to developmental differences in initial SSD, we ran a 3 (Age: children, adolescents and young adults) x 2 (SST: cool vs. hot) x 2 (Block: first vs. second) mixed-design ANOVA on the SSRTs.

3. RESULTS

The 3 (Age: children vs. adolescents vs. young adults) x 2 (SST: cool vs. hot) ANOVA on the SSRTs revealed a main effect of condition, $F(1, 209) = 6.02$, $p = .015$, $\eta^2_p = .03$, with longer SSRTs for hot trials relative to cool trials, a main effect of age, $F(2, 209) = 54.08$, $p < .001$, $\eta^2_p = .34$, with longer SSRTs in children than in adolescents ($p < .001$) and longer SSRTs in adolescents than in young adults ($p < .001$), but no two-way interaction between age and condition, $F < 1$ (see Figure 2). Although the two-way interaction between age and condition did not reach the significance, we conducted post hoc analyses, using Holm-Bonferroni correction, which revealed longer SSRTs in children than in young adults and in adolescents than in young adults in both the cool and hot SSTs (all $ps < .001$) and longer SSRTs in children than in adolescents in the cool SST ($p = .046$) but not in the hot SST ($p = .19$).



- Insert Figure 2 about here -

Figure 2: SSRTs for both cool (gray line) and hot (black line) SSTs for each age group. The error bars represent the standard error of the mean. * $p < .05$, ** $p < .01$, *** $p < .001$ (Holm-Bonferroni post hoc analyses).

Given that all participants started with the same stop signal delay, young adults might need more stop trials to reach their optimal SSD than children or adolescents. If so, developmental effects could be underestimated when analyzing jointly the data of the two blocks of trials. Thus, we ran a 3 (Age: children vs. adolescents vs. young adults) x 2 (SST: cool vs. hot) x 2 (blocks of trials: first vs. second) mixed-design ANOVA on the SSRTs. Importantly, we found a marginal three-way interaction between block, condition and age, $F(2, 209) = 2.69$, $p = .07$, $\eta^2_p = .02$. To characterize the three-way interaction, we ran separate ANOVAs for each block of trials.

For the first block, the 3 (Age: children vs. adolescents vs. young adults) x 2 (SST: cool vs. hot) ANOVA on the SSRTs revealed a main effect of age, $F(2, 209) = 47.26$, $p < .001$, η^2_p

= .31, but neither main effect of condition, $F < 1$, nor two-way interaction between age and condition, $F < 1$. For the second block, a similar ANOVA on the SSRTs revealed a main effect of condition, $F(1, 209) = 16.57, p < .001, \eta^2_p = .073$, with longer SSRTs for hot than cool trials, a main effect of age, $F(2, 209) = 20.43, p < .001, \eta^2_p = .16$, with longer SSRTs in children than in adolescents ($p = .011$) and longer SSRTs in adolescents than in young adults ($p = .002$), but no two-way interaction between age and condition, $F < 1$. Although the two-way interaction between age and condition did not reach the significance, we conducted post hoc analyses, using Holm-Bonferroni correction which revealed longer SSRTs in children than in adults in both the cool and hot SSTs (all $ps < .001$), longer SSRTs in adolescents than in young adults in the hot SSTs ($p = .006$) but not in the cool SST ($p = .75$) and marginally longer SSRTs in children than in adolescents in the cool SST ($p = .065$) but not in the hot SST ($p = .92$). Finally, hot SSRTs were longer than cool SSRTs in adolescents ($p = .009$).

4. DISCUSSION

In the present study, we investigated the development of the ability to stop an initiated motor response from late childhood to young adulthood in an affectively neutral or charged context using a cool and hot version of the SST, respectively. As expected and consistent with previous studies on both *interference control* (e.g., Aïte et al., 2018) and *response inhibition* abilities (e.g., Schel & Crone, 2013; Tillman et al., 2007), we found that the ability to inhibit an initiated motor response increases linearly with age from late childhood to young adulthood in an affectively neutral context. The development of this ability in an affectively charged context appears to be more protracted, with children and adolescents being less efficient at stopping an initiated motor response than young adults but with no developmental difference between children and adolescents. The developmental patterns in the cool and hot SSTs reported in the present study are consistent with Zelazo's developmental model of cool

and hot executive functions (Zelazo & Carlson, 2012), which assumes cool executive functions develop earlier than hot executive functions. The results of the post-hoc analyses conducted on the second block of trials tentatively support the imbalance model of adolescence (Casey, 2015; Casey & Caudle, 2013), which suggests that adolescents have specific difficulties resisting prepotent responses in an affectively charged context. Our results provide preliminary evidence that a negatively affectively charged context could affect selectively the ability to inhibit an initiated motor response in adolescents. However, this result needs to be interpreted with caution given that the two-way interaction between age and condition did not reach significance. Future studies need to replicate such adolescent specificity effect and investigate the extent to which this ability is also affected by a positive affectively charged context.. Indeed, adolescents might be less efficient to inhibit an initiated motor response in a positive affectively charged context because they are more sensitive to appetitive cues (e.g., rewards assignment) at the root of their risk seeking behaviors (e.g., alcohol and substance abuse, dangerous driving, practice of dangerous sports; Casey, Getz, & Galvan, 2008; Reyna & Farley, 2006). Consistent with this view, Somerville et al. (2011) reported less efficient response inhibition for happy faces than calm faces in a Go/NoGo task associated with an increased activity within the ventral striatum.

Importantly, consistent with previous studies in children, young adolescents (Urban et al. 2012) and adults (e.g., Kalanthroff et al., 2013), we found that an affectively charged context alters response inhibition abilities in children, adolescents and young adults, suggesting that the stop signals used in the hot SST produced an affectively charged context. The detrimental effect of an affectively charged context on response inhibition abilities could provide evidence that emotional stimuli may capture more attentional resources than neutral stimuli, leaving fewer processing resources available for the successful inhibition of motor responses (e.g., Kalanthroff et al., 2013).

A limitation of the present study is the cross-sectional design to assess the developmental trajectory of *response inhibition* abilities from late childhood to young adulthood in affectively neutral and charged contexts. The cross-sectional design typically does not provide information on the developmental rate of these abilities at the individual level and is prone to cohort effect which may be confounded with age-related effects (Setia, 2016). Using a between-subject design to study the development of inhibitory control in neutral and affectively charged contexts constitutes another limitation of the present study. A within-subject design would have allowed to control for potential difference in the inhibitory control efficiency of the participants assigned to the cool and the hot versions of the SST. Finally, we couldn't determine whether the effect of the affectively charged context on the SSRTs varied in function of the type of emotions elicited by the stop signal (i.e., fear vs anger) because the SSD in the hot SST was not adjusted throughout the blocks separately for anger and fear stop signal trials.

In conclusion, we provide the first evidence that *response inhibition* and, in particular, the ability to stop an initiated motor response develops linearly from late childhood to young adulthood in both neutral and affectively charged contexts, in line with a previous study conducted on children and young adolescents up to 13 years of age (Urban et al., 2012). The development of this ability in an affectively charged context appears to be more protracted than in an affectively neutral context. Also, analyses from the second block provide tentative evidence that adolescents have specific difficulties resisting prepotent responses in an affectively charged context. Finally, exerting response inhibition in affectively charged contexts is more challenging than in neutral contexts at all ages and might explain why it might be difficult to change people's behaviors during crises.

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