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Intraindividual Variability Is a Developmental Marker of Cool, Hot-Positive, and Hot-Negative Inhibitory Control

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The present study used a novel, well-controlled paradigm to investigate the development of cool, hot-positive, and hot-negative inhibitory control in a sample of children (6- to 11-year-old; $N = 38$, 21 females), adolescents (12- to 18-year-old; $N = 38$, 24 females), and adults (19- to 38-year-old; $N = 38$, 28 females; sample location: United Kingdom). An ex-Gaussian approach was employed on stop signal task data to distinctly examine for the first time how mean and intraindividual variability measures of inhibitory control are modulated at different time spans of development and neutral and socioaffective contexts. Results show a combination of adolescent-emergent, adolescent-specific, and adult-emergent patterns for distinct ex-Gaussian measures of cool, hot-positive, and hot-negative inhibition performance, suggesting a much more complex account of inhibitory control development than previously believed.

Public Significance Statement
The present study shows that the development of inhibitory control abilities from childhood to adulthood is much more complex than previously thought, with different developmental patterns across neutral, socially positive, and socially negative contexts. Moreover, this study suggests that intraindividual variability measures are sensitive markers of developmental changes in inhibitory control.

Keywords: intraindividual variability, cool inhibitory control, hot inhibitory control, development, ex-Gaussian modeling

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Inhibitory control abilities (i.e., the suppression of impulsive or habituated responses to achieve long-term goals; Diamond, 2013) are key for successful cognitive, social, and emotional development. Importantly, inhibitory control has been found to be particularly sensitive to the presence of socioaffective cues or contexts (Casey, 2015), but previous investigations on how inhibitory control in social contexts (i.e., hot inhibitory control) develops from childhood to adulthood have yielded mixed evidence: While some studies report a linear delayed trajectory (e.g., Prencipe et al., 2011; Tottenham et al., 2011), others report an adolescent-specific decline in such abilities (e.g., Dreyfuss et al., 2014; Somerville et al., 2011). One possibility is that these inconsistencies arise due to the use of task measures that assume a Gaussian distribution of reaction times (e.g., mean and *SD*), despite typical reaction time data being positively skewed. Instead, ex-Gaussian modeling of reaction times offers greater interpretative power by generating both mean and intraindividual variability measures: This finer level of analysis is key to identify differences that might not be apparent when looking at conventional Gaussian measures, and can provide greater insight into how the development of inhibitory control is modulated by socioaffective contexts. Moreover, only few studies discriminate between inhibitory control in hot-positive and hot-negative socioaffective contexts, although they might differently modulate inhibitory control across development. The present study thus aimed to investigate the development

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Roser Cañigueral served as lead for conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, supervision, visualization, writing–original draft, and writing–review and editing. Katherine Barron contributed equally to investigation and resources and served in a supporting role for formal analysis, methodology, and writing–original draft. Nikolaus Steinbeis served as lead for funding acquisition and supervision and served in a supporting role for conceptualization and writing–review and editing.

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of cool, hot-positive, and hot-negative inhibitory control across childhood, adolescence, and adulthood by employing an ex-Gaussian approach to examine both mean and intraindividual variability measures of inhibitory control. Note that hereafter we use the term “hot” to refer to both “hot-positive” and “hot-negative” contexts and make explicit differences between them where relevant.

The Development of Cool and Hot Inhibitory Control

Cognitive control supports flexible and goal-directed responses to environmental changes (Diamond, 2013) and is a reliable predictor of later life well-being (Moffitt et al., 2011). A core component of cognitive control is inhibitory control, which involves the suppression of impulsive or habitual responses in the pursuit of longer term goals (Diamond, 2013). Contrary to traditional experimental paradigms, in daily life inhibitory control is frequently embedded in socioaffective contexts: For instance, we will inhibit from checking our social media accounts in order to meet a work deadline. This has led to a distinction between inhibitory control in the presence of socioaffectively neutral cues or contexts (cool inhibitory control) and inhibitory control in the presence of socioaffectively charged cues or contexts (hot inhibitory control; Zelazo & Carlson, 2012), with supposedly distinct (but related) maturational changes in the brain (Berger et al., 2021; Fernández García et al., 2021; Moriguchi, 2022). While there is substantial evidence and broad agreement that cool inhibitory control has a protracted *linear* developmental trajectory, which reaches maturity in mid to late adolescence (Durston et al., 2002; Luna et al., 2010; van der Molen, 2000), the developmental pattern of hot inhibitory control remains largely unclear.

Two models have been proposed for the development of hot inhibitory control. The linear development model suggests that hot inhibitory control also develops linearly with age but, compared to cool inhibitory control, this development is delayed and the most significant improvements occur later in development (Grose-Fifer et al., 2013; Prencipe et al., 2011; Salvia et al., 2021; Schel & Crone, 2013; Tottenham et al., 2011; Zelazo & Carlson, 2012). The quadratic development model on the other hand suggests that hot inhibitory control follows a U-shaped trajectory, where adolescents show worse inhibition in the presence of socioaffectively charged cues compared to children and adults (Aïte et al., 2018; Dreyfuss et al., 2014; Poon, 2018; Somerville et al., 2011). In contrast to the linear model, the quadratic model describes an adolescent-specific developmental pattern of hot inhibitory control and is consistent with the imbalance model of brain development during adolescence (Casey et al., 2008). The so-called imbalance model poses that during this period there is an imbalance between a still immature (relative to adults) prefrontal network and a hyperactive emotional subcortical network, which results in a lack of top-down control of emotional responses as well as greater sensitivity to socioemotional salient events and contexts (Casey, 2015; Casey et al., 2008; Foulkes & Blakemore, 2016). Importantly, the imbalance model predicts nonlinear changes of behavior in socioaffective contexts during adolescence, either in the form of adolescent-specific patterns (i.e., quadratic trajectory) or adolescent-emergent patterns (i.e., asymptotic trajectory where major behavioral changes occur from childhood to adolescence and stabilize into adulthood; Casey, 2015; Somerville et al., 2013).

Evidence in favor of both linear and quadratic models has been reported in the past, but there are several limitations in the methods employed by these studies. First, the tasks used to compare cool and hot conditions are not always well-matched, in the sense that they are tapping into different executive functions, which in turn have their own developmental trajectories (Crone & Steinbeis, 2017). For example, a color-word Stroop task measuring inhibition is often used as a proxy for cool executive function (Poon, 2018; Prencipe et al., 2011); however, it is then compared to a hot condition using the Iowa Gambling task (Prencipe et al., 2011) or Cambridge Gambling task (Poon, 2018), which also require feedback monitoring abilities (Iowa Gambling task) and additionally measure decision-making and risk-taking behavior (Cambridge Gambling task). Second, some studies compare neutral versus affectively charged versions of traditional inhibition tasks that use words or faces as stimuli, such as the go/no-go task (Breiner et al., 2018; Cohen, Breiner, et al., 2016; Dreyfuss et al., 2014; Schel & Crone, 2013; Somerville et al., 2011; Tottenham et al., 2011), Flanker task (Grose-Fifer et al., 2013), or Stroop task (Aïte et al., 2018). However, these tasks also require the ability to correctly recognize and categorize emotions, which could influence response times or false alarms across development (Schulz et al., 2007). Moreover, these studies either collapse performance across various emotions (Aïte et al., 2018; Grose-Fifer et al., 2013) or focus on a single emotion (e.g., happy or fear; Dreyfuss et al., 2014; Somerville et al., 2011), with only a few studies discriminating between positive and negative valence (Cohen, Breiner, et al., 2016; Schel & Crone, 2013; Tottenham et al., 2011). For instance, in a Go-NoGo task, Schel and Crone (2013) found that inhibitory control performance was better for happy faces compared to fearful faces across all age groups. In contrast, Tottenham et al. (2011) found no differences between happy and fearful faces, although inhibition in these conditions was better relative to sad and angry faces. Cohen, Breiner, et al. (2016) also found that, compared to adults, adolescents and young adults showed poorer inhibition performance and decreased activity in cognitive control brain regions when presented with fearful faces (note there was no child group in this study). Interpretations from these studies are further limited by the fact that different age ranges are often used for adolescence, with some studies including individuals from 11 or 13 up to 17 years old (Grose-Fifer et al., 2013; Somerville et al., 2011), and others looking at subgroups with finer age ranges (Prencipe et al., 2011; Schel & Crone, 2013). Overall, it is still unclear if, and how, positive and negative inhibitory controls develop differently from childhood into adolescence and adulthood.

A final limitation in these studies is that the manipulations used to create a hot condition are based on isolated neutral or emotional stimuli with poor ecological validity. Cohen, Breiner, et al. (2016) also used unpredictable aversive noises or monetary rewards to induce negative or positive emotional states in participants, but these cues are still far from reflecting real-life socioaffective situations. Instead, using a manipulation that modulates the socioaffective context of the task might be closer to real-world daily situations requiring inhibitory control. Here we aimed to address these limitations to clarify the developmental patterns of cool and hot inhibitory control, by implementing a social context manipulation to generate cool, hot-positive, and hot-negative conditions, while using the same task and stimuli across all conditions (i.e., stop signal task with neutral faces).

Measuring Intraindividual Variability in Inhibitory Control

Another major aspect that could help explain discrepancies across studies looking at the development of cool and hot inhibitory control is the use of inhibition measures that show poor sensitivity to developmental differences. In particular, the overuse of mean scores for reaction time measures has been called into question since it may not be a reliable index for all cognitive processes (Heathcote et al., 1991; Whelan, 2008). For instance, it has been shown that cognitive performance is not stable within an individual but instead shows fluctuations across multiple timescales (Shalev et al., 2019), and these fluctuations may index aspects of cognitive processing that cannot be detected by mean scores (Whelan, 2008). Thus, there has recently been an increased interest in intraindividual variability measures of reaction times.

Importantly, intraindividual variability of cognitive performance can reflect both adaptive and maladaptive processes (Allaire & Marsiske, 2005; Li et al., 2004; Siegler, 1994). For instance, intraindividual variability of cognitive performance is generally considered adaptive during childhood because it allows the testing and acquisition of new strategies that lead to positive development; instead, it is considered maladaptive in adulthood and the elderly, where it reflects a decline in cognitive function. In line with this, it has been shown that intraindividual variability in reaction time follows a U-shape across the lifespan, where variability is high in childhood, decreases into young adulthood (reflecting optimization of cognitive performance), and increases again in the elderly (MacDonald et al., 2006; Williams et al., 2005). However, to the best of our knowledge, no previous study has investigated how the development of intraindividual variability measures of cognitive performance is modulated by socioaffective contexts that are positively or negatively valenced.

When drawing interpretations of intraindividual variability of cognitive performance as reflecting adaptive or maladaptive processes, it is also important to consider how it relates to task performance. For instance, greater intraindividual variability may reflect maladaptive processes if it is predictive of worse task performance: In this case, higher intraindividual variability may indicate poor attention or task engagement (resulting in poorer performance), while lower intraindividual variability may reflect greater attentional engagement with the task at hand. Equally, greater intraindividual variability may reflect adaptive processes if it predicts better task performance: Here, higher intraindividual variability may be indicative of higher adaptation to varying task demands, whereas lower intraindividual variability may reflect no adaptation to the environment. Thus, in order to meaningfully interpret the patterns of intraindividual variability in our data in terms of adaptive and maladaptive processes, we also aimed to investigate how individual differences in task performance relate to intraindividual variability measures across neutral, positive, and negative socioaffective contexts.

Previous studies measuring intraindividual variability in reaction times have mostly used variability measures that assume a Gaussian distribution in reaction time data, such as the *SD* or coefficient of variation. However, an important feature of reaction times is that they are positively skewed and therefore follow a non-Gaussian distribution. In particular, ex-Gaussian distributions resemble a closer fit to typical reaction time data, since they combine a Gaussian and exponential distribution: By distinguishing between these two components, ex-Gaussian distributions offer a much finer level of analysis with greater interpretative power than conventional measures (Luce, 1986; Matzke et al., 2013, 2017; McAuley et al., 2006). In this sense, a key advantage of ex-Gaussian distributions is that they generate three parameters of interest which arguably reflect distinct aspects of cognitive processing: The mu parameter corresponds to the mean of the Gaussian distribution, which reflects average processing speed in task performance (e.g., mean of the stop signal reaction time [SSRT] distribution, indicating mean inhibition reaction time); the sigma parameter corresponds to the *SD* of the Gaussian distribution and reflects variability in processing speed (e.g., *SD* of the SSRT distribution, indicating variability in inhibition reaction times); finally, the tau parameter corresponds to the mean and *SD* of the exponential distribution (skewness or tail of the distribution), which reflects the degree and variability of occasional extremely slow responses (i.e., extremely slow task performance). Importantly, ex-Gaussian parameters are a descriptive tool of reaction time data and do not map onto specific cognitive processes; therefore, cognitive interpretations of such parameters should be cautious (Matzke & Wagenmakers, 2009). The present paper employed ex-Gaussian parameters (mu, sigma, and tau) from the SSRT distribution to examine the development of cool and hot inhibitory control.

The Present Study

The present study aimed to investigate the development of cool and hot inhibitory control across childhood, adolescence, and adulthood by employing an ex-Gaussian approach to generate mean and intraindividual variability measures of task performance. To do so, we used a paradigm where participants played three rounds of two consecutive games. First, participants played a Tetris task inspired by M. Lee et al. (2018) where, for each round, they were shown the face of a different confederate (with neutral expression) and were instructed to play in a neutral, cooperative, or competitive way. Second, they played the stop signal task using the same faces shown in the Tetris task as go and stop stimuli. Thus, although a neutral face was used in all three rounds of the stop signal tasks, each round varied in socioaffective context and thus allowed us to measure cool, hot-positive, and hot-negative inhibitory control, respectively.

Prior to analyzing the development of cool and hot inhibitory control, we aimed to test the relation between mean inhibitory processing speed (mu) and intraindividual variability measures (sigma and tau) in order to identify whether greater intraindividual variability reflects adaptive or maladaptive processes. Previous interpretations of sigma and tau suggest that, while greater sigma reflects poorer overall task engagement, greater tau is specifically linked to lapses in attention and transient periods of inefficient task performance (Hervey et al., 2006; Karalunas et al., 2014; West et al., 2002). Consistent with these interpretations, we expected that mu and sigma, and mu and tau, would be positively correlated, meaning that greater variability is related to slower reaction times and so is maladaptive. Instead, a negative correlation would mean greater variability is related to faster reaction times, thus reflecting adaptive processes.

Our hypotheses were the following. In line with previous studies (Durston et al., 2002; Luna et al., 2010; van der Molen, 2000; Williams et al., 2005), we hypothesized that cool inhibitory control would show a linear improvement in mean processing speed from childhood to adulthood and that intraindividual variability would linearly decrease with age (note that we did not expect to find a U-shape since our sample did not include older adults). In contrast, and in line with the imbalance model of adolescence (Casey et al., 2008), we expected that hot inhibitory control would show a quadratic relation with age, whereby mean processing speed would be worse in adolescence compared to childhood and adulthood (Aïte et al., 2018; Dreyfuss et al., 2014; Poon, 2018; Somerville et al., 2011), and intraindividual variability would reflect adolescent-specific maladaptive processes: Note that we did not have a specific hypothesis on whether this would be in the form of a U-shape or inverted U-shape pattern, since it would depend on the relation found between mean processing speed and intraindividual variability. In line with Schel and Crone (2013) and Tottenham et al. (2011), we expected that adults and children would show better mean processing speed and greater adaptive-like variability in the hot-positive condition compared to the neutral and hot-negative condition; however, according to findings by Somerville et al. (2011), we considered the possibility that adolescents would show worse mean processing speed and greater maladaptive-like variability in the hot-positive condition compared to neutral and hot-negative conditions. Finally, consistent with the findings by Cohen, Breiner, et al. (2016), we expected that adults would show better mean processing speed and greater adaptive-like variability in the hot-negative condition compared to adolescents and children. Note that across our hypotheses we did not have specific predictions about different patterns for sigma and tau and expected them to be overall similar.

Materials and Method

Participants

An a priori power calculation suggested that a sample size of 38 participants in each age group would be required to reach a power of 0.8 at a 0.05 level of significance. This calculation used an estimated medium-to-large effect size of $\eta_p^2 = 0.08$, based on the results of Aïte et al. (2018) for the interaction effect between age group (children, adolescents, and adults) and condition (cool or hot cognitive control). Thus, a group of 38 children, 38 adolescents, and 38 adults completed the study; note children and adolescents were categorized in each age group based on their school year within the British education system (children: Year 1 to Year 6; adolescents: Year 7 to Year 11). However, two children were excluded from all analyses (i.e., Tetris task and stop signal task) because they did not correctly complete the questionnaires (including demographics information). A number of participants (18 children, 10 adolescents, and 18 adults) were additionally excluded from the stop signal task analysis because their performance on the stop signal task failed to meet specified inclusion criteria (detailed in the Materials and Method section Stop Signal Task; see the Discussion section “Strengths, Limitations, and Future Directions” for considerations on data attrition). Demographic information for the Tetris task analysis sample and the stop signal task analysis sample are summarized in Table 1.

Children were recruited via the authors’ lab database; adolescents were recruited from a high school in South London; and adults were recruited via the authors’ university online database, which includes students and nonstudents (note that psychology students were excluded from recruitment to reduce the chance of prior knowledge related to the aims of the study). Formal consent was obtained from the parents of child and adolescent participants, as well as from adolescent and adult participants. Participants were compensated for participation in the study with a £15 voucher for use at a popular bookstore in the United Kingdom. The study was granted ethical approval by the local Research Ethics Committee.

Face Stimuli

To introduce the social manipulation, we created three confederates. Photos of three actresses were selected from the Radboud Faces Database (Langner et al., 2010): Three young adult faces were chosen for the tasks to be completed by adolescents and adults, and three child faces were chosen for the tasks to be completed by children (see S1 in the online supplemental materials). Note that young adult faces were chosen for the adolescent group as there were no available adolescent faces in the Radboud Faces Database at the time of the study, and children faces would look very young for this group. The names Emily, Lily, and Chloe were randomly chosen, and each was assigned to a photo. Selection of photos was limited to White females, as this was the gender group we expected to make up the majority of our sample. Neutral faces with 95% or greater agreement for emotion classification were chosen (Langner et al., 2010). Photos were also chosen on the basis that they had been similarly rated as demonstrating positive affect because neutral faces can be interpreted as negative and we did not want this potential perception to interfere with the social aspects of the task (E. Lee et al., 2008; Marusak et al., 2017; Rollins et al., 2021).

Tetris Task

The Tetris task was adapted from M. Lee et al. (2018) to create affectively neutral, positive, and negative social contexts, so each participant played the Tetris task three times, once for each condition. In each condition, a picture of the confederate was displayed at the top left of the screen (neutral face looking straight-ahead), a Tetris-like block template with squares missing on the bottom row was displayed in the central area of the screen, and below the template two block configurations were presented—one that would fill the space on the bottom row of the template, and one that would not (Figure 1A). On each trial, participants could choose either the block configuration on the left by pressing the left arrow key, or the block configuration on the right by pressing the down arrow key. For each condition, there was a total of 10 trials: Five trials requiring a participant response interspersed with five trials requiring a confederate response, in order to enhance reciprocity.

Crucially, the instructions on how participants could score points differed across conditions (see S2.1 in the online supplemental materials for instructions given on each condition). In the cool condition (neutral context), participants were simply instructed to score points by choosing the block that they wished. After each participant response, the message “you chose a block” would appear. Then, the confederate would choose a block and the message “(confederate’s name) chose a block” would appear. In the hot-positive condition (cooperative context), participants were told that they and the other player should help each other score points by choosing the block that completed the bottom row. This time the message “you helped (confederate’s name)” appeared after each correct participant response, and vice versa after each confederate response. If the participant did not choose the block that completed the bottom row, the message “you did not help (confederate’s name)” appeared instead. Finally, in the hot-negative condition (competitive context), participants were told that they and the other player should “block” each other by choosing the block that did not complete the bottom row. The message “you blocked

Table 1
Participant Demographics

	Tetris task analysis sample				Stop signal task analysis sample			
Group	*N*	Gender	Age: *M* (*SD*)	Age range	*N*	Gender	Age: *M* (*SD*)	Age range
Children	36	21 F, 15 M	9.15 (1.27)	6–11.3	18	13 F, 5 M	9.48 (1.13)	6–11
Adolescents	38	24 F, 14 M	14.22 (1.76)	11.7–18.1	28	17 F, 11 M	13.91 (1.72)	11.7–18.1
Adults	38	28 F, 10 M	25.68 (4.67)	19.3–38.2	20	15 F, 5 M	24.84 (4.78)	19.3–38.2

Note. F = female; M = male.

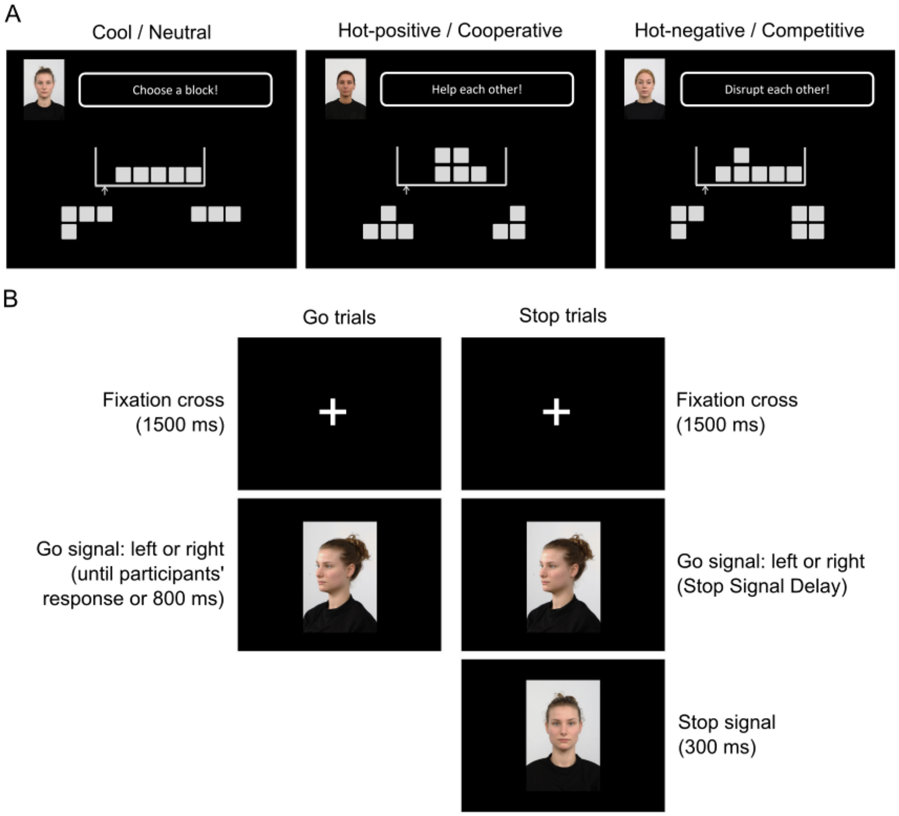
(confederate's name)" appeared after each correct participant response, and the message "you did not block (confederate's name)" appeared after incorrect responses.

To assess the success of our social manipulation, after each round of the Tetris task participants were asked to rate on a Likert scale how much they liked the confederate, how exciting the game was with the confederate, and how interesting the game was with the confederate (0 = *not at all*, 8 = *very much*; see S2.1.5 in the online supplemental materials for a description of the questions). They were told that their rating would not be shared with the other player.

Stop Signal Task

To measure cool and hot inhibitory control, we used a variation of the stop signal task that used pictures of faces as stimuli (Marino et al., 2015; Figure 1B). The pictures of faces corresponded to those used for the confederates in the neutral, cooperative, and competitive conditions of the Tetris task (Figure 1A). This design resulted in three conditions for the stop signal task: cool, hot-positive, and hot-negative, respectively. The hot-positive and hot-negative conditions were intended to measure hot inhibitory control because we expected the faces of the corresponding confederate to elicit a positive or negative

Figure 1
Screenshots of the Tasks



Note. (A) Example of Tetris task for each condition. (B) Sample go and stop trials for the stop signal task with faces. Photos are reproduced from the Radboud Faces Database (Langner et al., 2010). See the online article for the color version of the figure.

social context based on their prior interaction in the Tetris task. In contrast, the cool condition was intended to measure cool inhibitory control, because we did not expect this face to be associated with a valenced social context, or at the very least not to be as valenced as either of the other two contexts. This way, the cool and hot inhibitory control tasks differed only in social context and were thus highly comparable.

For each condition, each trial started with a picture of the corresponding confederate facing to the left or to the right (go signal), and participants were instructed to respond as fast as possible to the direction of the face (see S2.2 in the online supplemental materials for instructions given): If the stimulus was facing to the left, participants were instructed to press the left arrow key, and if the stimulus was facing to the right, participants were instructed to press the down arrow key. On go trials (75% of the total trials), the picture of the confederate disappeared when participants responded or after 800 ms (Figure 1B). After this, a fixation cross was presented for 1,500 ms. On stop trials (25% of the total trials), the go signal was immediately followed by a stop signal, which corresponded to a picture of the confederate facing straight-ahead (Figure 1B) and was displayed for 300 ms. In the presence of a stop signal, participants were instructed not to respond to the go signal, thus requiring them to inhibit the go signal response. The delay between the presentation of the go signal and the stop signal (i.e., stop signal delay [SSD]) was adjusted to participants' performance using an adaptive staircase procedure: At the beginning of the task the SSD was set at 200 ms; when participants successfully inhibited their response then the SSD was increased by 50 ms to make the task more difficult; when participants were not able to inhibit their response then the SSD was decreased by 50 ms to make the task easier. This adjustment is meant to guarantee a 50% inhibition success and avoid floor or ceiling effects (inhibition success: $M = 58.63\%$; minimum = 45%; maximum = 70%). Participants completed three rounds of the stop signal task (one for each condition; order of conditions was counterbalanced across participants), with each round containing 80 trials.

The traditional measure of interest on the stop signal task is the SSRT, and we first calculated this measure according to the horse-race model of stopping (Logan & Cowan, 1984) and the integration method (i.e., with replacement of go omissions; Verbruggen et al., 2019) to aid in our exclusion criteria. Following this procedure, we first determined the maximum reaction time for correct go responses and replaced go omission trials with this value. Next, we rank-ordered all reaction times for go responses and determined the percentage of failed inhibitions: The go reaction time that corresponded to this percentage was determined (*n*th GoRT). Finally, we computed the SSRT as the difference between the nth GoRT and the mean SSD. Participants with a negative SSRT and those with less than 50% correct go responses in at least one condition were excluded from further analyses for all measures (18 children, 10 adolescents, and 18 adults; see S3 and Table S3-1 in the online supplemental materials for a breakdown of how many participants were excluded based on each SSRT exclusion criterion). Intraindividual variability in SSRTs was then estimated using a hierarchical Bayesian parametric approach (BPA) implemented with the Dynamic Models of Choice software (Heathcote et al., 2019; Matzke et al., 2013). The BPA assumes that SSRTs form an ex-Gaussian distribution and uses Markov Chain Monte Carlo sampling of the observed participant stop signal task data in order to estimate the three parameters that describe the SSRT distribution: mu, sigma, and tau (Matzke et al., 2013).

Experimental Procedure

All participants completed the experiment online using their personal computers. Upon registering to the study, participants/parents were instructed to complete a questionnaire on Qualtrics (www.qualtrics.com). This questionnaire included the consent form, questions about the participants' age and gender, a question about whether the participant knew how to play Tetris.

Participants were then instructed to complete the experimental tasks on Pavlovia (www.pavlovia.com), which were designed using PsychoPy3 (Peirce et al., 2019). All instructions given throughout the experiment were presented both in writing and with audio recorded by the experimenters, using language that could be understood by the youngest participants (see S2 in the online supplemental materials). Participants first completed a practice round of five trials for the Tetris task, and a practice round of 12 trials for the stop signal task. For the stop signal task practice, participants had to respond correctly to at least seven trials of any type (go or stop) to make sure they correctly understood the task instructions; otherwise, they were redirected back to the instructions for the stop signal task and completed the practice round again, for up to three times (only a minority of the participants failed at the practice round: All children performed well already at the first practice round; four adolescents completed the practice round twice, and one adolescent completed the practice round three times; one adult completed the practice round twice). The set of face pictures used in the practice rounds was different than the ones used for the main experimental rounds but was selected following the same criteria.

Participants then completed the three conditions sequentially: the order of the conditions was counterbalanced along with the confederate assigned to each condition, such that there were 18 possible combinations of condition order and confederate. Note that, after participants were excluded from the analyses, there were 14 counterbalancing conditions represented across the children group, 17 counterbalancing conditions represented across the adolescent group, and 16 counterbalancing conditions represented across the adult group. We considered that the counterbalancing was still optimal for the purposes of the present study, since all possible condition orders and all possible combinations of confederates assigned to each condition were still represented within each age group.

At the start of each condition, participants were told that they would play the two games they practiced with another player. A screen popped up with the message "waiting for other player," before introducing them to one of the three confederates (Emily, Lily, or Chloe). Then participants played the Tetris task (with the posttask ratings) and the stop signal task using pictures of the corresponding confederate's face as stimuli. Once they had finished all the tasks, participants rated on a Likert scale how sure they were that the confederates on the Tetris task were real (0 = *not at all*, 8 = *very much*).

Upon completing the study, all participants or parents were debriefed via email about the purpose of the study.

Statistical Analyses

Questionnaire and task data were cleaned using MATLAB (R2021a, MathWorks) and analyzed with R (R Core Team, 2017), using the lme4 and lmerTest packages (Bates et al., 2015; Kuznetsova et al., 2017). Both the analyses of the Tetris task and the stop signal task were first run with the samples described in the

Participants section, and then additionally excluding outliers based on the 1.5 × IQR (Interquartile Range) criterion (Tetris task: six children, eight adolescents, four adults detected as outliers only for Tetris performance measure; stop signal task: four children, one adolescents, and three adults detected as outliers). The pattern of results was the same between both methods for all analyses, so we report results using the samples with no excluded outliers. Note that for all analyses age was used as a categorical variable (i.e., children, adolescents, and adults) instead of a continuous predictor: since age ranges were much larger for adults than for children and adolescents, and the distribution of age across the three age groups was skewed, using age as a continuous predictor would otherwise lead to skewed developmental patterns (see S4 and Figure S4-1 in the online supplemental materials).

To evaluate if our social manipulation was effective and test for potential differences across age groups, we fitted linear mixed models with likeability ratings, interest ratings, excitement ratings as dependent variables, group (children, adolescents, adults) as between-subject factor, and condition (neutral, positive, negative) as within-subject factor. The same linear mixed model was fitted with Tetris performance as dependent variable (i.e., proportion of correct participant responses) to test for differences between age groups and conditions. For all models, post hoc pairwise comparisons using Bonferroni's adjustment were computed.

To determine whether intraindividual variability reflected adaptive or maladaptive processes, Bonferroni-corrected Pearson correlations were run between mu (mean processing speed) and sigma (variability in processing speed) as well as between mu and tau (degree and variability of occasional extremely slow responses) for each age group and condition. Bonferroni-corrected Pearson correlations between sigma and tau were also run to test how these two measures of variability relate to each other. Note that we also tested whether these correlations held after controlling for age, and whether they were moderated by age; however, because age was a nonsignificant covariate and did not moderate the correlations it was not included in any analysis. We further tested whether mu, sigma, and tau are associated with age for each age group and condition, and this analysis is reported in S5 in the online supplemental materials.

To test effects of age group and condition on inhibition, we fitted linear mixed models with mu, sigma, and tau as dependent variables, group as between-subject factor, condition as within-subject factor, and proportion of correct go responses as covariate. For all models, post hoc pairwise comparisons using Bonferroni's adjustment were computed. Note that likeability, interest and excitement ratings, Tetris performance, and belief on whether the confederate in the Tetris task was real, were nonsignificant covariates for all models and did not yield changes in the pattern of results, so they were not included in any analysis. We also tested whether results held after controlling for gender; however, because gender did not moderate any of the effects of interest it was not included in any analysis.

Data and study materials will be made available upon request.

Results

Manipulation Checks

To validate that our social manipulation was effective, we evaluated the ratings of participants after each Tetris task round (see S6 and Table S6-1 in the online supplemental materials for descriptives). For likeability ratings (Figure 2A), there was a main effect of group—$F(2, 109) = 4.99$, $p = .008$: Adolescents rated the confederate as less likeable compared to children, $t(109) = 2.63$, $p = .029$, $d_z = 0.574$, and adults, $t(109) = 2.82$, $p = .017$, $d_z = 0.607$. There was also a main effect of condition—$F(2, 218) = 22.2$, $p < .001$—where likeability ratings were greater for the positive confederate compared to the neutral, $t(218) = 3.23$, $p = .004$, $d_z = 0.431$, and negative, $t(218) = 3.44$, $p < .002$, $d_z = 0.891$, confederates, and greater for the neutral confederate compared to the negative confederate, $t(218) = 3.44$, $p = .002$, $d_z = 0.460$. There was an interaction effect between group and condition—$F(4, 218) = 2.71$, $p = .031$: Post hoc pairwise comparisons showed the neutral confederate was rated as less likeable by adolescents compared to adults, $t(262) = 2.96$, $p = .010$, $d_z = 0.845$, and the negative confederate was rated as less likeable by adolescents compared to children, $t(262) = 3.47$, $p = .002$, $d_z = 1.00$; moreover, adolescents rated the positive confederate as more likeable than the neutral, $t(218) = 2.72$, $p = .021$, $d_z = 0.625$, and negative, $t(218) = 4.94$, $p < .001$, $d_z = 1.13$, confederates, while adults rated the negative confederate as less likeable than the neutral, $t(218) = 3.86$, $p < .001$, $d_z = 0.886$, and positive, $t(218) = 5.11$, $p < .001$, $d_z = 1.17$, confederates.

For interest ratings (Figure 2B), there was a main effect of group—$F(2, 108.6) = 12.93$, $p < .001$—indicating that adolescents rated the task as less interesting compared to children, $t(109) = 4.81$, $p < .001$, $d_z = 1.38$, and adults, $t(109) = 3.81$, $p < .001$, $d_z = 1.07$. There was no main effect of condition—$F(2, 216) = 2.90$, $p = .057$—nor interaction effect between group and condition—$F(4, 216) = 0.271$, $p = .896$.

For excitement ratings (Figure 2C), there was a main effect of group—$F(2, 109) = 14.15$, $p < .001$—indicating that adolescents rated the task as less exciting compared to children, $t(109) = 5.29$, $p < .001$, $d_z = 1.53$, and adults, $t(109) = 3.07$, $p = .008$, $d_z = 0.878$. There was no main effect of condition—$F(2, 218) = 1.169$, $p = .312$—nor interaction effect between group and condition—$F(4, 218) = 0.939$, $p = .442$.

We also evaluated differences in Tetris performance across age groups and social conditions (Figure 2D). There was a main effect of condition—$F(2, 218) = 7.78$, $p < .001$—indicating that Tetris performance was worse in the negative condition compared to the neutral, $t(218) = 2.46$, $p = .043$, $d_z = 0.329$, and positive, $t(218) = 3.90$, $p < .001$, $d_z = 0.522$, conditions. There was no main effect of group—$F(2, 109) = 2.63$, $p = .076$—nor interaction effect between group and condition—$F(4, 218) = 0.244$, $p = .913$.

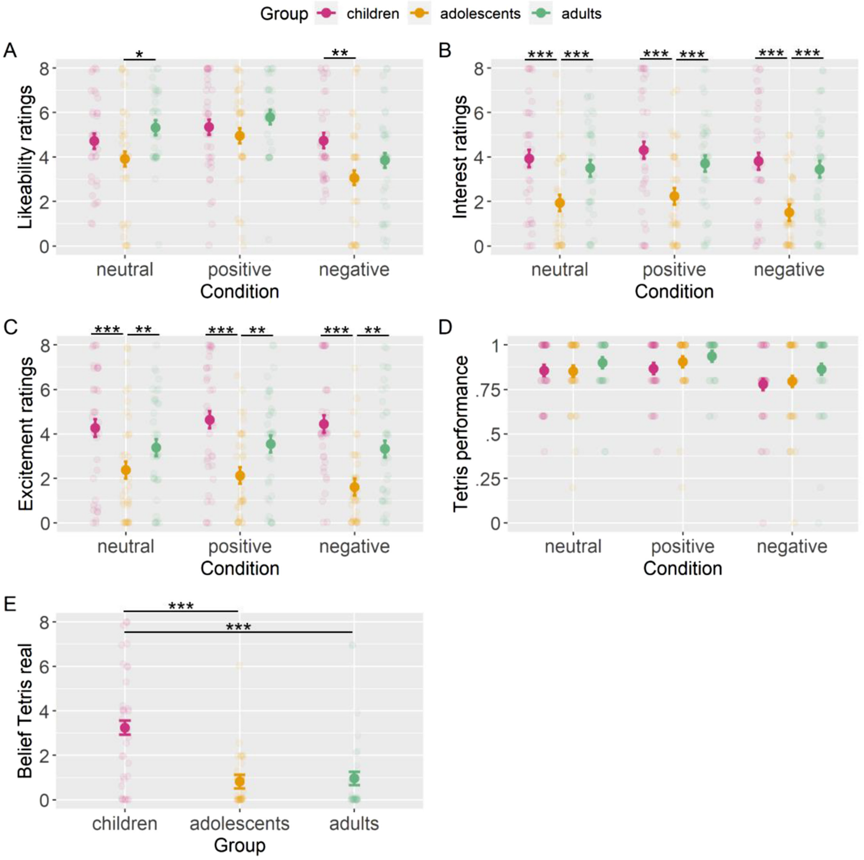
To further assess the strength of our manipulation, we tested for group-related effects on the participants' belief that the confederates in the Tetris task were real (Figure 2E). There was a main effect of group—$F(2, 109) = 19.32$, $p < .001$—where children held a greater belief that the confederates were real compared to adolescents, $t(109) = 5.56$, $p < .001$, $d_z = 1.29$, and adults, $t(109) = 5.24$, $p < .001$, $d_z = 1.22$.

Correlations Between Inhibitory Control Measures

For correlations between mu (mean processing speed) and sigma (variability in processing speed; Figure 3A), no correlations were significant (all $ps > .6$). For correlations between mu and tau (degree and variability of occasional extremely slow responses; Figure 3B), all correlations were significant (all $ps < .001$) and positive (all $r > .80$), indicating that greater variability is related to worse mean processing

Figure 2

Plots for Manipulation Checks and Tetris Performance: Estimated Marginal Mean (Filled Circle), SE (Error Bars), and Raw Datapoints (Shaded Circles)



Note. (A) Likeability ratings. (B) Interest ratings. (C) Excitement ratings. (D) Tetris performance. (E) Belief that confederates in the Tetris task were real. See the online article for the color version of the figure.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

speed (longer reaction times). For correlations between sigma and tau, adolescents-neutral, adults-neutral, and adults-positive were significant ($p < .02$) and positive ($r > .50$); all other correlations were not significant (all ps $> .1$).

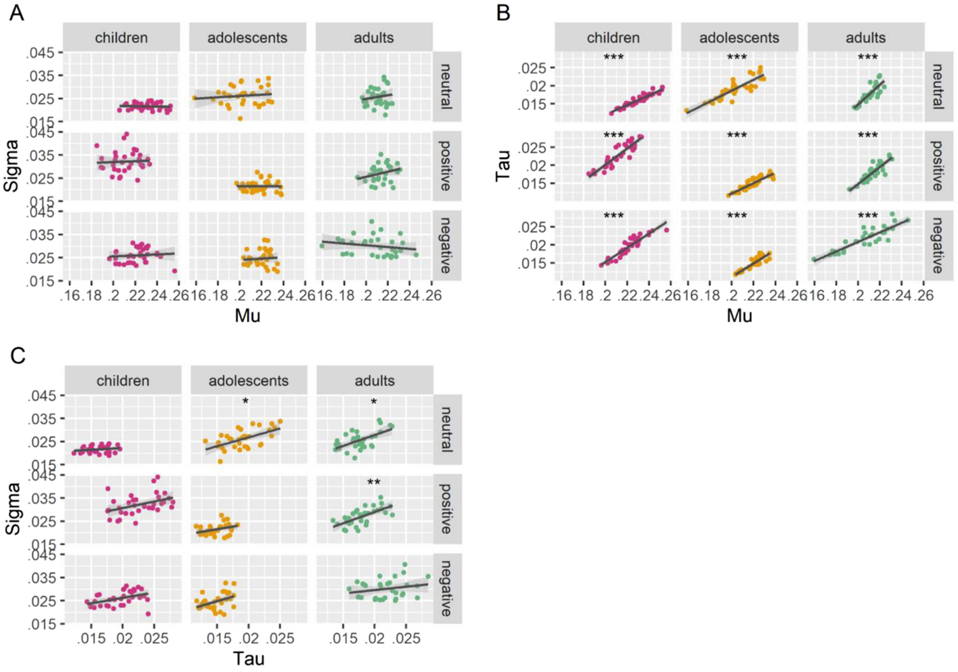
Effects of Age Group and Social Context on Inhibitory Control

We tested the effects of age group and condition on three measures of inhibitory control: mu, sigma, and tau (see S6 and Table S6-2 in the online supplemental materials for descriptives; see also Table S6-3 in the online supplemental materials for descriptives on additional measures from the stop signal task). For mu (mean processing speed; Figure 4A), there was a main effect of group—$F(2, 60.7) = 3.33$, $p = .042$: Children performed worse than adults, $t(64.8) = 2.54$, $p = .041$, $d_z = 0.553$. There was no main effect of condition—$F(2, 122.7) = 0.127$, $p = .880$—but there was an interaction effect between group and condition—$F(4, 123.3) = 14.5$, $p < .001$. Post hoc pairwise comparisons showed that, for the neutral condition, children performed worse than adolescents, $t(185) = 5.78$, $p < .001$, $d_z = 1.83$, and adults, $t(185) = 3.46$, $p = .002$, $d_z = 1.19$; for the positive condition, children performed better than adolescents, $t(184) = 3.11$, $p = .006$, $d_z = 0.999$; for the negative condition, adults performed better than children, $t(184) = 3.09$, $p = .007$, $d_z = 1.07$, and adolescents, $t(185) = 3.98$, $p < .001$, $d_z = 1.22$. Moreover, children performed better in the positive condition than in the neutral condition, $t(126) = 4.67$, $p < .001$, $d_z = 1.56$; adolescents performed better in the neutral condition than in the positive, $t(127) = 4.74$, $p < .001$, $d_z = 1.27$, and negative, $t(126) = 4.47$, $p < .001$, $d_z = 1.19$, conditions; adults performed better in the negative condition compared to the positive condition, $t(127) = 2.82$, $p = .017$, $d_z = 0.895$. The proportion of correct go responses was a significant covariate—$F(1, 110.2) = 5.04$, $p = .027$.

For sigma (variability in processing speed; Figure 4B), there was a main effect of group—$F(2, 63.2) = 14.5$, $p < .001$: Adults' performance was more variable than for children, $t(64.6) = 2.53$, $p = .041$, $d_z = 0.515$, and adolescents, $t(62.2) = 5.38$, $p < .001$, $d_z = 0.948$. There was a main effect of condition—$F(2, 125.5) = 7.51$, $p < .001$—where performance in the neutral condition was less variable than in the positive, $t(126) = 3.43$, $p = .002$, $d_z = 0.608$,

Figure 3

Correlation Plots Between Inhibitory Control Measures for Each Age Group and Condition



Note. (A) Mu (mean processing speed) and sigma (variability in processing speed). (B) Mu and tau (degree and variability in occasional extremely slow responses). (C) Sigma and tau. See the online article for the color version of the figure.

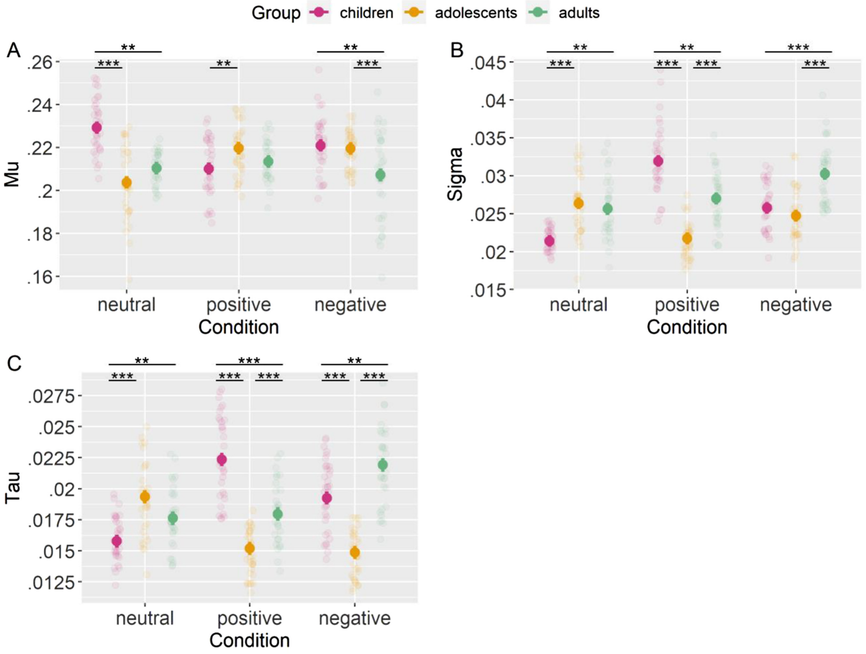
* $p < .05$. ** $p < .01$. *** $p < .001$.

and negative conditions, $t(126) = 3.28$, $p = .004$, $d_z = 0.582$. There was also an interaction effect between group and condition—$F(4, 125.9) = 22.3$, $p < .001$. Post hoc pairwise comparisons showed that, for the neutral condition, children were less variable than adolescents, $t(187) = 4.09$, $p < .001$, $d_z = 1.26$, and adults, $t(187) = 3.56$, $p = .001$, $d_z = 1.19$; for the positive condition, children were more variable than adolescents, $t(187) = 7.93$, $p < .001$, $d_z = 2.48$, and adults, $t(187) = 3.25$, $p = .004$, $d_z = 1.08$, and adults were more variable than adolescents, $t(188) = 4.70$, $p < .001$, $d_z = 1.39$; for the negative condition, adults were more variable than children, $t(187) = 4.27$, $p < .001$, $d_z = 1.44$, and adolescents, $t(188) = 5.09$, $p < .001$, $d_z = 1.52$. Moreover, children's performance was less variable in the neutral condition than in the positive, $t(126) = 7.83$, $p < .001$, $d_z = 2.61$, and negative, $t(126) = 2.84$, $p = .016$, $d_z = 0.948$, conditions, as well as less variable in the negative condition compared to the positive condition, $t(126) = 4.99$, $p < .001$, $d_z = 1.66$; adolescents' performance was less variable in the positive condition than in the neutral, $t(127) = 4.21$, $p < .001$, $d_z = 1.13$, and negative, $t(127) = 2.73$, $p = .022$, $d_z = 0.732$, conditions; adults' performance was more variable in the negative condition compared to the neutral, $t(126) = 3.77$, $p < .001$, $d_z = 1.19$, and positive, $t(127) = 2.69$, $p = .024$, $d_z = 0.853$, conditions. The proportion of correct go responses was not a significant covariate—$F(1, 106.6) = 2.52$, $p = .115$.

For tau (degree and variability of occasional extremely slow responses; Figure 4C), there was a main effect of group—$F(2, 61.46) = 21.7$, $p < .001$: The degree and variability in extremely slow responses were lower for adolescents than for children, $t(64.1) = 4.28$, $p < .001$, $d_z = 0.814$, and adults, $t(62.2) = 6.25$, $p < .001$, $d_z = 1.12$. There was no main effect of condition—$F(2, 123.7) = 1.75$, $p = .177$—but there was an interaction effect between group and condition—$F(4, 124.2) = 33.9$, $p < .001$. Post hoc pairwise comparisons showed that, for the neutral condition, the degree and variability in extremely slow responses was lower for children than for adolescents, $t(187) = 5.04$, $p < .001$, $d_z = 1.56$, and adults, $t(187) = 2.99$, $p = .009$, $d_z = 1.01$; for the positive condition, the degree and variability in extremely slow responses was greater for children than for adolescents, $t(187) = 8.08$, $p < .001$, $d_z = 2.54$, and adults, $t(187) = 3.96$, $p < .001$, $d_z = 1.32$, and greater for adults than for adolescents, $t(187) = 4.06$, $p < .001$, $d_z = 1.21$; for the negative condition, the degree and variability in extremely slow responses was greater for adults than for children, $t(186) = 3.62$, $p = .001$, $d_z = 1.23$, and adolescents, $t(187) = 8.98$, $p < .001$, $d_z = 2.69$, and greater for children than for adolescents, $t(187) = 4.73$, $p < .001$, $d_z = 1.47$. Moreover, the degree and variability in extremely slow responses were lower for children in the neutral condition than in the positive, $t(126) = 7.39$, $p < .001$, $\mathrm{d_z} = 2.46$, and negative, $t(126) = 3.54$, $p = .002$, $d_z = 1.18$, conditions, as well as in the negative condition compared to the positive condition, $t(126) = 3.85$, $p < .001$, $d_z = 1.28$; the degree and variability in extremely slow responses were greater for adolescents in the neutral condition than in the positive, $t(127) = 6.10$, $p < .001$, $d_z = 1.64$, and negative, $t(126) = 6.93$, $p < .001$, $d_z = 1.29$, conditions; the degree and variability in extremely slow responses were greater for adults in the negative condition compared to the neutral,

Figure 4

Plots for Inhibition Measures: Estimated Marginal Mean (Filled Circle), SE (Error Bars), and Raw Datapoints (Shaded Circles)



Note. (A) Mu (mean processing speed). (B) Sigma (variability in processing speed). (C) Tau (degree and variability in occasional extremely slow responses). See the online article for the color version of the figure.
$^{*} p < .05$. $^{**} p < .01$. $^{***} p < .001$.

$t(126) = 4.42$, $p < .001$, $d_z = 1.39$, and positive, $t(127) = 3.99$, $p < .001$, $d_z = 1.27$, conditions. The proportion of correct go responses was a significant covariate—$F(1, 105.9) = 10.9$, $p = .001$.

Discussion

We investigated the development of cool and hot inhibitory control across childhood, adolescence, and adulthood by assessing both mean (reflecting average processing speed in task performance) and intraindividual variability (reflecting variable and occasional extremely slow response inhibition) measures. To do so, we introduced a novel manipulation to generate neutral, positive, and negative social contexts of inhibitory control; moreover, we used for the first time an ex-Gaussian approach to measure mean performance and intraindividual variability in the context of hot inhibitory control. We found that cool inhibitory control is characterized by adolescent-emergent patterns in mean and variable task performance, as well as adolescent-specific changes in occasional extremely slow response inhibition. For hot-positive inhibitory control, we observed a decline among adolescents in mean task performance, as well as adolescent-specific modulations for variable and occasional extremely slow response inhibition. Instead, for hot-negative inhibitory control there were adult-emergent patterns for mean and variable task performance, and adolescent-specific changes in occasional extremely slow response inhibition. While these findings are overall supportive of the imbalance model of adolescence (Casey, 2015; Casey et al., 2008), they also suggest a much more complex account of the development of inhibitory control and further highlight ex-Gaussian measures of response inhibition as sensitive markers of developmental changes in inhibitory control.

Manipulation Checks

Inspired by M. Lee et al. (2018) we implemented, for the first time, a manipulation of the social context of inhibitory control to generate cool, hot-positive, and hot-negative conditions, while using the same task and stimuli across all conditions and age groups. In line with M. Lee et al. (2018), performance in the Tetris task was overall better in the positive and neutral conditions than in the negative condition. As argued by M. Lee et al. (2018), a positive/cooperative context is related to stronger activation of the mentalizing network (compared to a negative/competitive context) so this could lead to greater task engagement and, in turn, better performance in this condition. A more plausible explanation is that it is just easier to perform the task under the neutral and positive conditions, which require the default response of choosing the block that fits in the template, than under the negative condition, which requires inhibition of the default response to choose the block that does not fit in the template. Posttask ratings showed that all groups of participants rated the confederate in the hot-positive condition as most likeable and the confederate in the hot-negative condition as least likeable, indicating that our manipulation was effective in creating different social contexts for inhibition. We also found that this pattern was exacerbated for the positive condition in the adolescent group, and for the negative condition in the adult group, although children did not show any differences: A possible reason why we do not find the same significant effects across conditions within each age group could be related to limited power to detect these effects on subjective ratings (note the a priori power calculation to determine sample size was based on group by condition effects on cognitive performance); however note that, within each age group, the same pattern of ratings is found across conditions (Figure 2A). Moreover, adolescents rated the tasks as less interesting and exciting than children and adults: given that adolescents are particularly sensitive to the presence of peers and this heightens the value of nonsocial rewards (Foulkes & Blakemore, 2016), it could be that performing the tasks in isolation was not as rewarding for adolescents as for children and adults. Another possibility is that there are some social factors relating to the age mismatch between the confederate (young adult) and adolescent participants that could influence overall engagement toward the games. For instance, a previous study shows that task performance among younger adolescents is differently modulated when observed by the experimenter (i.e., an adult) or when observed by a peer (i.e., a same-age friend; Wolf et al., 2015). Furthermore, children believed that the confederates in the Tetris task were real more so than adolescents and adults. Importantly, despite the between-group differences reported above, these measures were nonsignificant covariates in our statistical models for inhibitory control and did not yield changes in the pattern of results, indicating that such differences were not responsible for any of the effects found on inhibitory control performance.

Developmental Effects on Cool, Hot-Positive, and Hot-Negative Inhibitory Control

In order to meaningfully interpret the patterns of intraindividual variability in our data in terms of adaptive or maladaptive processes, we tested how individual differences in mu (mean processing speed) relate to intraindividual variability measures of sigma (variability in processing speed) and tau (degree and variability of occasional extremely slow responses). Results showed that there was a significant positive relation between mu and tau for all age groups and conditions, indicating that better processing speed (faster inhibition reaction times) predicts reduced degree and variability of occasional extremely slow response inhibition. This is consistent with the notion that increased tau reflects lapses in attention and transient periods of inefficient task performance, and therefore is maladaptive (Hervey et al., 2006; Karalunas et al., 2014; West et al., 2002). Moreover, these correlations held after controlling for age and were not moderated by age, indicating that these associations are true across development. However, no significant relationship was found between mu and sigma for any age group and condition, which makes it hard to robustly interpret whether the patterns of sigma reflect adaptive or maladaptive processes. Note, however, that the developmental patterns observed across sigma and tau are overall very similar (see Figure 4: same pattern for neutral and positive conditions, while the negative condition shows an adult-emergent pattern for sigma and an adolescent-specific pattern for tau), and that sigma and tau were positively related for some age groups and conditions: This suggests that increased variability in inhibitory control performance is likely to also reflect maladaptive processes.

Results showed that cool inhibitory control performance (mu) improved from childhood to adolescence and that performance levels were maintained from adolescence to adulthood. Similarly, intraindividual variability as measured by sigma and tau increased from childhood to adolescence and stabilized into adulthood. Therefore, in a neutral social context adolescent inhibitory control is characterized by adult-like levels of average, variable, and occasional extremely slow performance. This pattern of results is partially consistent with previous studies reporting a linear improvement in cool inhibitory control performance from childhood to adolescence and adulthood (Aïte et al., 2018; Poon, 2018; Prencipe et al., 2011; Zelazo & Carlson, 2012), although we find that performance levels stabilize into adulthood. These findings are thus most consistent with an adolescent-emergent pattern, where major changes in inhibitory control happen from childhood to adolescence, and are further supported by neuroimaging studies showing that brain regions underlying inhibitory control reach maturity during adolescence (Durston et al., 2002; Luna et al., 2010; van der Molen, 2000).

For hot inhibitory control in a positive social context, results showed that mean processing speed (mu) was best in children and worsened into adolescence, although there were no differences with the adult group. This finding is partially in line with previous studies showing that hot inhibitory control worsens into adolescence (Aïte et al., 2018; Dreyfuss et al., 2014; Somerville et al., 2011), although it does not provide enough evidence on how it will change into adulthood. Intraindividual variability as measured by sigma and tau was lowest in the adolescent group compared to children and adults, indicating that task performance variability and occasional extremely slow response inhibition were particularly reduced in adolescence. This adolescent-specific pattern of hot-positive inhibitory control is consistent with a quadratic model of hot inhibitory control and the imbalance model of adolescence (Casey, 2015; Casey et al., 2008). In this case, greater sensitivity toward the cooperative interaction with the confederate may enhance the adolescents' engagement with the task and reduce lapses of attention, while the lack of top-down control of emotional responses might result in worse inhibitory control performance.

For hot inhibitory control in a negative social context, results showed that mean processing speed improved from childhood and adolescence into adulthood. These findings are partially consistent with previous studies reporting a delayed linear development of hot inhibitory control from childhood to adulthood (Poon, 2018; Prencipe et al., 2011; Schel & Crone, 2013; Zelazo & Carlson, 2012): However, here we find that greatest changes happen from adolescence to adulthood, suggesting an adult-emerging, rather than linear, pattern for hot inhibitory control in negative social contexts. Intraindividual variability as measured by sigma also followed an adult-emergent pattern, with increased variability in adulthood compared to childhood and adolescence. Therefore, in a hot-negative social context adolescent inhibitory control is still characterized by child-like levels of average and variable performance. However, patterns of tau were consistent with an adolescent-specific pattern, where the adolescent group showed a reduction in occasional extremely slow response inhibition compared to children and adults. These nonlinear changes in behavior are in line with the imbalance model of adolescence (Casey, 2015; Casey et al., 2008): While greater sensitivity toward the competitive interaction with the confederate might keep adolescents engaged with the task and reduce attentional lapses, the lack of top-down control of emotional responses might result in child-like levels of inhibitory control performance. Moreover, the different developmental patterns found for sigma (adult-emergent) and tau (adolescent-specific) highlight that these two components of inhibitory control (reflecting task engagement and attentional lapses, respectively) are differently engaged in childhood, indicating that the neurocognitive mechanisms subserving these functions have distinct sensitivity to negative social contexts early in development.

Social Context Effects on Childhood, Adolescent, and Adult Inhibitory Control

The different developmental patterns found for cool, hot-positive, and hot-negative inhibitory control also yield interesting insights for each age group. For instance, children showed best inhibitory processing speed for the positive condition compared to adolescents, as well as compared to the neutral condition. This finding is consistent with the results from Schel and Crone (2013) and Tottenham et al. (2011) who found that inhibitory control performance was best for positively valenced stimuli (i.e., happy faces). However, while they found this pattern was true across all age groups, we find it is specific to the children group: It could be that adolescent and adult participants are more sensitive to the ecologically valid neutral and negative socioaffective contexts used in our study than to the isolated neutral and negative facial stimuli used by previous studies, so they show greater improvements in inhibitory control under those conditions, respectively. Moreover, children also showed greatest variability for the positive condition (followed by the negative condition) compared to the other age groups and conditions, which yields two possible interpretations. On the one hand, it may be that children show increased variability under a positive social situation due to increased recruitment of attentional resources to process the socioaffective environment rather than the task at hand. On the other hand, it has been suggested that increased variability in children may reflect greater testing and acquisition of new strategies when completing a task (MacDonald et al., 2009), so it could be that a positive social context encourages children to try out different strategies. However, we found that greater variability as measured by tau is related to worse inhibitory processing speed, so whether greater exploration of strategies in childhood leads to better inhibitory control performance at later ages warrants further investigation.

For the adolescent group, in line with previous studies, we find that the presence of a positive or negative social context interferes with inhibitory control abilities (as measured by mean task performance). We also report for the first time that variable and occasional extremely slow response inhibition are markedly reduced under such contexts, likely reflecting increased engagement and attention. Thus, our findings suggest that, during adolescence, social contexts differently modulate distinct aspects of inhibitory control, for instance by reducing inhibitory processing speed or increasing attention. Importantly, these findings are in line with the notion that adolescence is a period of both risks and opportunities (Dahl, 2004), with vulnerability for negative behaviors (e.g., risk-taking) but also prospects for positive healthy development (e.g., prosocial behavior; Blankenstein et al., 2020; Casey, 2015; Chein et al., 2011; Chen, 2000; Do et al., 2017; Gardner & Steinberg, 2005). In this sense, our findings could have implications for educational and clinical settings, where it should be carefully considered how courses or interventions might involve peer-based activities to enhance engagement of adolescents and in turn improve their outcomes.

Finally, adults showed best inhibitory processing speed in the negative condition compared to children and adolescents, as well as compared to the positive condition. This finding is in line with Cohen, Breiner, et al. (2016), who further showed that better inhibitory control performance under negative emotional states in adults is paralleled by increased functional connectivity between cognitive and emotional brain regions. The finding that adults show better inhibitory processing speed in the hot-negative condition could be because the competitive social context is interpreted as threatening and becomes a source of stress. In this sense, prior research looking at inhibitory control under conditions of sustained threat seems mostly in line with our results. In a number of studies, better inhibitory control performance on go/no-go tasks was seen when anxiety was induced with a mild electric shock or aversive auditory stimulus (Cantelon et al., 2019; Cohen, Dellarco, et al., 2016; Kim et al., 2021). Another recent study using the stop signal task under threat of electric shock has found similar results (Choi & Cho, 2020; although see also Roxburgh et al., 2019 for conflicting results). In the context of real-world stressful situations, enhanced inhibitory control abilities might contribute to the attenuation of affectively driven reactions that would otherwise lead to unfavorable consequences (e.g., not quitting job responsibilities during periods of heavy workload, and instead working persistently through all tasks). Such adult-specific enhancement of hot-negative inhibitory control might be due to the fact that, in earlier developmental periods, the prefrontal network is still immature and the emotional subcortical network is hyperactive, overall resulting in poorer affective and cognitive regulation (Casey, 2015; Casey et al., 2008; Foulkes & Blakemore, 2016). Importantly, adults also showed greater intraindividual variability for the negative condition compared to the other age groups and conditions, suggesting that the presence of a stressor in the form of a competitive situation also reduces task engagement and induces more lapses of attention. One possibility is that, because stressful contexts are cognitively demanding, more cognitive resources will be invested in coping with such demands and therefore attentional resources available for the task at hand will decrease (e.g., during periods of heavy workload, it is often harder to focus on tasks; Scott et al., 2015). Note, however, that such reduction in attentional resources does not affect overall inhibitory control performance, which in adults is subserved by fully mature prefrontal and subcortical networks (Casey, 2015).

To sum up, we first implemented a correlational analysis to establish, at the individual level, the relation between a well-known measure of inhibitory control (mu, or mean performance) and two novel intraindividual variability measures (sigma and tau), and thus provide a functional interpretation of such measures. This analysis shows that greater intraindividual variability is related to worse mean levels of inhibition, indicating that increments in intraindividual variability reflects a maladaptive process. Then, we tested at the group level how the social–affective manipulation modulates mu, sigma, and tau across age groups: These results provide insight into how different components of inhibitory control (e.g., processing speed, attention) change as a function of social context and development. Interestingly, our results show that in some cases there may be group-level improvements in mean response inhibition but declines in intraindividual variability (e.g., adult group in the negative condition), or vice versa (e.g., adolescent group in the positive condition).

Although somewhat complex, these group-level findings are not necessarily inconsistent with the individual-level findings from the correlations, where improvements in mean response inhibition are related to improvements in intraindividual variability. Critically, while individual-level analyses indicate a relation between two measures, group-level analyses indicate fluctuations of these measures under specific manipulations, but such fluctuations are not necessarily related.

Overall, our findings suggest a much more complex picture of the development of inhibitory control than previously believed, with distinct patterns for socially neutral and socially valanced contexts, as well as for measures of mean, variable, and occasional extreme task performance. Importantly, by employing an ex-Gaussian approach on reaction time data from the stop signal task we were able to identify finer developmental patterns of cool, hot-positive, and hot-negative inhibitory control than previously reported. In particular, we show that such developmental patterns span beyond simple accounts of linear versus quadratic models, with a combination of adolescent-emergent, adolescent-specific, and adult-emergent patterns for distinct measures of inhibitory control performance. These findings overall indicate that ex-Gaussian measures of response inhibition are particularly sensitive markers of developmental changes in inhibitory control, although how social context modulations on these measures map onto specific cognitive mechanisms remains to be seen.

Strengths, Limitations, and Future Directions

The present study introduces a novel and effective manipulation to generate cool, hot-positive, and hot-negative social contexts of inhibitory control. Importantly, this manipulation overcomes longstanding limitations in previous studies, for instance by relying on the generation of affectively charged social contexts (instead of using isolated emotional stimuli with poor ecological validity), by using the same stimuli across social contexts, or by discriminating between hot-positive and hot-negative social contexts. Moreover, the present study highlights how using ex-Gaussian parameters to measure different aspects of inhibitory control performance (mean inhibitory processing speed, variability in processing speed, and occasional extremely slow response inhibition) is crucial to reveal fine-grained individual differences across development and social contexts that would be overlooked by conventional measures. It is worth noting that ex-Gaussian parameters are a descriptive tool of reaction time data and do not map onto specific cognitive processes; therefore, some caution should be taken when making cognitive interpretations of such parameters (Matzke & Wagenmakers, 2009). A possible explanation is that, contrary to other models such as drift diffusion models (DDMs), ex-Gaussian distributions do not consider response accuracy, which makes it hard to distinguish between effects of task difficulty or response caution on ex-Gaussian parameters. Instead, although DDM grants a more straightforward link between parameters and underlying psychological processes, it can only be applied to go responses and therefore offers little insight into stop responses (i.e., inhibitory control). Future studies that use a combination of ex-Gaussian and DDM parameters. Future research using tasks with reaction time data would benefit from using a combined ex-Gaussian and DDM approach where possible, as it will provide a richer picture of the developmental pattern of the cognitive process of interest. For instance, future studies might test if these findings are replicated on other types of inhibitory control (e.g., interference control, proactive control) or executive functions (e.g., cognitive flexibility, working memory).

Some limitations should also be considered. For instance, a potential caveat in our social manipulation is that, in the Tetris task, the negative condition required participants to choose the wrong block, which could in itself be considered a task of inhibitory control. This potential priming could have carryover effects on the subsequent stop signal task, leading to better inhibitory control performance in the negative condition relative to the neutral or positive conditions. However, the fact that there is not a general improvement in inhibitory control performance for the negative condition relative to the neutral or positive conditions suggests this is unlikely. Moreover, it is unclear whether the negative social context is established because of the competitive context or because the Tetris task is harder under the negative condition (as participants need to choose the wrong block instead of the default response). Our data show that during the Tetris task participants performed worst in the negative condition (suggesting the negative condition is indeed harder), but also that they rated the confederate in the negative condition as least likeable (suggesting that the competitive context successfully leads to a negative perception of the confederate). Thus, it is likely that both aspects played a role in generating the negative social context. Future studies may try different versions of this social manipulation that do not give the instruction to choose the "wrong" block in the Tetris task to fully exclude such carryover and confounding effects. For example, participants could be instructed to score points by choosing the block that they wish (like the neutral condition), but they must try and score more points than the confederate to win the game; the game could be further manipulated to enhance its competitive aspect, for instance by showing to participants that the confederate is earning more points than they do over the trials.

Furthermore, our experimental design did not include assessments of how well the affectively charged social contexts transferred from the Tetris task to the stop signal task, or if there were any differences in such transfer across age groups. Although we included likeability, excitement, and interest ratings after the Tetris task in each condition, these ratings did not directly assess the effect of our manipulation during the stop signal task or on the emotional state of participants. We encourage future studies using socioaffective manipulations on the stop signal task to include ratings that reliably measure the effect of their manipulation and the emotional state of participants several times during the stop signal task. Another question that arises from our results is if there was any habituation to the socioaffective nature of the facial stimuli over the course of the stop signal task. To address this, analyses on the stop signal task could be performed separately on the first and second half of the task to check for any differences in the pattern of results over time. Unfortunately, given our task design the number of trials included in each half-task analysis (40 trials) would be too small to model reliable inhibitory control measures (Verbruggen et al., 2019). However, we run an analysis using the mean reaction time of correct go trials (meanGoRT) as a proxy of how facial stimuli is processed over time, and found no differences in meanGoRT between first and second half of the task (see S7 in the online supplemental materials). This finding suggests that there was no habituation to the socioaffective nature of the facial stimuli during the stop signal task, although future studies with higher number of trials will be needed to test if this is also true for inhibition measures.

Another limitation in the present study is that around half of the children and adults in our sample, and around one fourth of adolescents, did not perform the stop signal task over chance level. Such high levels of poor performance among participants may be explained by the fact that the study happened online, so participants might have been more disengaged from the task or more distracted by the home environment than it would normally be expected in a supervised lab setting. However, a recent study suggests that, with appropriate precautions such as those taken in the present study (e.g., incentivizing task completion, including audible task instructions or providing clear instruction about technological and environment requirements), results from online studies reliably replicate those from in-person studies (Nussenbaum et al., 2020). Another possibility is that it is harder for participants to perform the stop signal task with face stimuli than with the traditional nonsocial stimuli, since monitoring faces and direct gaze are cognitively demanding (Beattie, 1981; Doherty-Sneddon et al., 2001; Glenberg et al., 1998; Markson & Paterson, 2009). The high rate of exclusion also means that our study was likely underpowered for the analyses of the stop signal task; therefore, the present findings should be interpreted with caution and warrant future replications with larger sample sizes. Moreover, while the adaptive staircase procedure guarantees an inhibition success rate of 50%, we found that inhibition success ranged between 45% and 70%. Interestingly, participants with higher inhibition success took longer to respond in go trials, indicating that they were implementing proactive control strategies by strategically slowing down their responses and waiting for the stop signal (Verbruggen & Logan, 2008; see S8 in the online supplemental materials).

Finally, the developmental patterns described are based on a cross-sectional sample, which bars tests of how processing speed and lapses in attention at a given age and social context may be related to improvements or declines at later ages. Moreover, we were not able to test for linear or quadratic developmental trends because the uneven distribution of our sample across age groups would lead to skewed developmental patterns. Future studies with robust longitudinal samples will be needed to clarify the relation between these processes throughout development.

Conclusion

To conclude, the present study is the first to examine how mean and intraindividual variability measures of cool, hot-positive, and hot-negative inhibitory control are modulated across development. Results show that developmental patterns for mean, variable, and occasional extremely slow inhibitory control performance span beyond simple accounts of linear versus quadratic models. We found that cool inhibitory control is characterized by adolescent-emergent patterns in mean and variable processing speed, as well as in occasional extremely slow response inhibition. For hot-positive inhibitory control, we observed a decline among adolescents in mean processing speed, as well as adolescent-specific modulations for variable and occasional extremely slow response inhibition. Instead, for hot-negative inhibitory control, there were adult-emergent patterns for mean and variable processing speed, and adolescent-specific changes in occasional extremely slow response inhibition. Overall, these findings are in line with the imbalance model of adolescence, although they also suggest a more sophisticated account of inhibitory control development than previously believed. Importantly, these findings also indicate that ex-Gaussian measures of response inhibition are particularly sensitive markers of developmental changes in inhibitory control.

References

Aïte, A., Cassotti, M., Linzarini, A., Osmont, A., Houdé, O., & Borst, G. (2018). Adolescents' inhibitory control: Keep it cool or lose control. *Developmental Science*, *21*(1), Article e12491. https://doi.org/10.1111/desc.12491

Allaire, J. C., & Marsiske, M. (2005). Intraindividual variability may not always indicate vulnerability in elders' cognitive performance. *Psychology and Aging*, *20*(3), 390–401. https://doi.org/10.1037/0882-7974.20.3.390

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Beattie, G. W. (1981). A further investigation of the cognitive inference hypothesis of gaze patterns during conversation. *British Journal of Social Psychology*, *20*(4), 243–248. https://doi.org/10.1111/j.2044-8309.1981.tb00493.x

Berger, P., Friederici, A. D., & Wiesmann, C. G. (2021). *Maturation of distinct neural components of the cognitive control network support early development of inhibitory control*. bioRxiv. https://doi.org/10.1101/2021.07.02.450852

Blankenstein, N. E., Telzer, E. H., Do, K. T., van Duijvenvoorde, A. C. K., & Crone, E. A. (2020). Behavioral and neural pathways supporting the development of prosocial and risk-taking behavior across adolescence. *Child Development*, *91*(3), e665–e681. https://doi.org/10.1111/cdev.13292

Breiner, K., Li, A., Cohen, A. O., Steinberg, L., Bonnie, R. J., Scott, E. S., Taylor-Thompson, K., Rudolph, M. D., Chein, J., Richeson, J. A., Dellarco, D. V., Fair, D. A., Casey, B. J., & Galván, A. (2018). Combined effects of peer presence, social cues, and rewards on cognitive control in adolescents. *Developmental Psychobiology*, *60*(3), 292–302. https://doi.org/10.1002/dev.21599

Cantelon, J. A., Giles, G. E., Eddy, M. D., Haga, Z., Mahoney, C. R., Taylor, H. A., & Davis, F. C. (2019). Exerting cognitive control under threat: Interactive effects of physical and emotional stress. *Emotion*, *19*(7), 1236–1243. https://doi.org/10.1037/emo0000509

Casey, B. J. (2015). Beyond simple models of self-control to circuit-based accounts of adolescent behavior. *Annual Review of Psychology*, *66*(1), 295–319. https://doi.org/10.1146/annurev-psych-010814-015156

Casey, B. J., Getz, S., & Galvan, A. (2008). The adolescent brain. *Developmental Review*, *28*(1), 62–77. https://doi.org/10.1016/j.dr.2007.08.003

Chein, J., Albert, D., O'Brien, L., Uckert, K., & Steinberg, L. (2011). Peers increase adolescent risk taking by enhancing activity in the brain's reward circuitry. *Developmental Science*, *14*(2), F1–F10. https://doi.org/10.1111/j.1467-7687.2010.01035.x

Chen, L.-H. (2000). Carrying passengers as a risk factor for crashes fatal to 16- and 17-year-old drivers. *JAMA*, *283*(12), Article 1578. https://doi.org/10.1001/jama.283.12.1578

Choi, J. M., & Cho, Y. S. (2020). Beneficial effect of task-irrelevant threat on response inhibition. *Acta Psychologica*, *202*, Article 102980. https://doi.org/10.1016/j.actpsy.2019.102980

Cohen, A. O., Breiner, K., Steinberg, L., Bonnie, R. J., Scott, E. S., Taylor-Thompson, K. A., Rudolph, M. D., Chein, J., Richeson, J. A., Heller, A. S., Silverman, M. R., Dellarco, D. V., Fair, D. A., Galván, A., & Casey, B. J. (2016). When is an adolescent an adult? Assessing cognitive control in emotional and nonemotional contexts. *Psychological Science*, *27*(4), 549–562. https://doi.org/10.1177/0956797615627625

Cohen, A. O., Dellarco, D. V., Breiner, K., Helion, C., Heller, A. S., Rahdar, A., Pedersen, G., Chein, J., Dyke, J. P., Galvan, A., & Casey, B. J. (2016). The impact of emotional states on cognitive control circuitry and function. *Journal of Cognitive Neuroscience*, *28*(3), 446–459. https://doi.org/10.1162/jocn_a_00906

Crone, E. A., & Steinbeis, N. (2017). Neural perspectives on cognitive control development during childhood and adolescence. *Trends in Cognitive Sciences*, *21*(3), 205–215. https://doi.org/10.1016/j.tics.2017.01.003

Dahl, R. E. (2004). Adolescent brain development: A period of vulnerabilities and opportunities. Keynote address. *Annals of the New York Academy of Sciences*, *1021*(1), 1–22. https://doi.org/10.1196/annals.1308.001

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Do, K. T., Guassi Moreira, J. F., & Telzer, E. H. (2017). But is helping you worth the risk? Defining prosocial risk taking in adolescence. *Developmental Cognitive Neuroscience*, *25*, 260–271. https://doi.org/10.1016/j.dcn.2016.11.008

Doherty-Sneddon, G., Bonner, L., & Bruce, V. (2001). Cognitive demands of face monitoring: Evidence for visuospatial overload. *Memory and Cognition*, *29*(7), 909–919. https://doi.org/10.3758/BF03195753

Dreyfuss, M., Caudle, K., Drysdale, A. T., Johnston, N. E., Cohen, A. O., Somerville, L. H., Galván, A., Tottenham, N., Hare, T. A., & Casey, B. J. (2014). Teens impulsively react rather than retreat from threat. *Developmental Neuroscience*, *36*(3–4), 220–227. https://doi.org/10.1159/000357755

Durston, S., Thomas, K. M., Yang, Y., Ulug, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, *5*(4), F9–F16. https://doi.org/10.1111/1467-7687.00235

Fernández García, L., Merchán, A., Phillips-Silver, J., & Daza González, M. T. (2021). Neuropsychological development of cool and hot executive functions between 6 and 12 years of age: A systematic review. *Frontiers in Psychology*, *12*, Article 687337. https://doi.org/10.3389/fpsyg.2021.687337

Foulkes, L., & Blakemore, S.-J. (2016). Is there heightened sensitivity to social reward in adolescence? *Current Opinion in Neurobiology*, *40*, 81–85. https://doi.org/10.1016/j.conb.2016.06.016

Gardner, M., & Steinberg, L. (2005). Peer influence on risk taking, risk preference, and risky decision making in adolescence and adulthood: An experimental study. *Developmental Psychology*, *41*(4), 625–635. https://doi.org/10.1037/0012-1649.41.4.625

Glenberg, A. M., Schroeder, J. L., & Robertson, D. A. (1998). Averting the gaze disengages the environment and facilitates remembering. *Memory and Cognition*, *26*(4), 651–658. https://doi.org/10.3758/BF03211385

Grose-Fifer, J., Rodrigues, A., Hoover, S., & Zottoli, T. (2013). Attentional capture by emotional faces in adolescence. *Advances in Cognitive Psychology*, *9*(2), 81–91. https://doi.org/10.5709/acp-0134-9

Heathcote, A., Lin, Y. S., Reynolds, A., Strickland, L., Gretton, M., & Matzke, D. (2019). Dynamic models of choice. *Behavior Research Methods*, *51*(2), 961–985. https://doi.org/10.3758/s13428-018-1067-y

Heathcote, A., Popiel, S. J., & Mewhort, D. J. (1991). Analysis of response time distributions: An example using the Stroop task. *Psychological Bulletin*, *109*(2), 340–347. https://doi.org/10.1037/0033-2909.109.2.340

Hervey, A. S., Epstein, J. N., Curry, J. F., Tonev, S., Eugene Arnold, L., Keith Conners, C., Hinshaw, S. P., Swanson, J. M., & Hechtman, L. (2006). Reaction time distribution analysis of neuropsychological performance in an ADHD sample. *Child Neuropsychology*, *12*(2), 125–140. https://doi.org/10.1080/09297040500499081

Karalunas, S. L., Geurts, H. M., Konrad, K., Bender, S., & Nigg, J. T. (2014). Annual Research Review: Reaction time variability in ADHD and autism spectrum disorders: Measurement and mechanisms of a proposed transdiagnostic phenotype. *Journal of Child Psychology and Psychiatry*, *55*(6), 685–710. https://doi.org/10.1111/jcpp.12217

Kim, A. J., Lee, D. S., & Anderson, B. A. (2021). The influence of threat on the efficiency of goal-directed attentional control. *Psychological Research*, *85*(3), 980–986. https://doi.org/10.1007/s00426-020-01321-4

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). Lmertest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13

Langner, O., Dotsch, R., Bijlstra, G., Wigboldus, D. H. J., Hawk, S. T., & van Knippenberg, A. (2010). Presentation and validation of the Radboud Faces Database. *Cognition and Emotion*, *24*(8), 1377–1388. https://doi.org/10.1080/02699930903485076

Lee, E., Kang, J. I., Park, I. H., Kim, J.-J., & An, S. K. (2008). Is a neutral face really evaluated as being emotionally neutral? *Psychiatry Research*, *157*(1–3), 77–85. https://doi.org/10.1016/j.psychres.2007.02.005

Lee, M., Ahn, H. S., Kwon, S. K., & Kim, S. (2018). Cooperative and cCompetitive cContextual eEffects on sSocial cCognitive and eEmpathic nNeural rResponses. *Frontiers in Human Neuroscience*, *12*(June), 1–17. https://doi.org/10.3389/fnhum.2018.00218

Li, S.-C., Huxhold, O., & Schmiedek, F. (2004). Aging and attenuated processing robustness. *Gerontology*, *50*(1), 28–34. https://doi.org/10.1159/000074386

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91*(3), 295–327. https://doi.org/10.1037/0033-295X.91.3.295

Luce, R. D. (1986). *Response times: Their role in inferring elementary mental organization*. Oxford University Press.

Luna, B., Padmanabhan, A., & O'Hearn, K. (2010). What has fMRI told us about the development of cognitive control through adolescence? *Brain and Cognition*, *72*(1), 101–113. https://doi.org/10.1016/j.bandc.2009.08.005

MacDonald, S. W. S., Li, S.-C., & Bäckman, L. (2009). Neural underpinnings of within-person variability in cognitive functioning. *Psychology and Aging*, *24*(4), 792–808. https://doi.org/10.1037/a0017798

MacDonald, S. W. S., Nyberg, L., & Bäckman, L. (2006). Intra-individual variability in behavior: Links to brain structure, neurotransmission and neuronal activity. *Trends in Neurosciences*, *29*(8), 474–480. https://doi.org/10.1016/j.tins.2006.06.011

Marino, B. F. M., Mirabella, G., Actis-Grosso, R., Bricolo, E., & Ricciardelli, P. (2015). Can we resist another person's gaze? *Frontiers in Behavioral Neuroscience*, *9*(September), 1–12. https://doi.org/10.3389/fnbeh.2015.00258

Markson, L., & Paterson, K. B. (2009). Effects of gaze-aversion on visual-spatial imagination. *British Journal of Psychology*, *100*(3), 553–563. https://doi.org/10.1348/000712608X371762

Marusak, H. A., Zundel, C. G., Brown, S., Rabinak, C. A., & Thomason, M. E. (2017). Convergent behavioral and corticolimbic connectivity evidence of a negativity bias in children and adolescents. *Social Cognitive and Affective Neuroscience*, *12*(4), 517–525. https://doi.org/10.1093/scan/nsw182

Matzke, D., Dolan, C. V., Logan, G. D., Brown, S. D., & Wagenmakers, E.-J. (2013). Bayesian Parametric estimation of stop-signal reaction time distributions. *Journal of Experimental Psychology: General*, *142*(4), 1047–1073. https://doi.org/10.1037/a0030543

Matzke, D., Love, J., & Heathcote, A. (2017). A Bayesian approach for estimating the probability of trigger failures in the stop-signal paradigm. *Behavior Research Methods*, *49*(1), 267–281. https://doi.org/10.3758/s13428-015-0695-8

Matzke, D., & Wagenmakers, E. J. (2009). Psychological interpretation of the ex-Gaussian and shifted wald parameters: A diffusion model analysis. *Psychonomic Bulletin and Review*, *16*(5), 798–817. https://doi.org/10.3758/PBR.16.5.798

McAuley, T., Yap, M., Christ, S. E., & White, D. A. (2006). Revisiting inhibitory control across the life span: Insights from the ex-Gaussian distribution. *Developmental Neuropsychology*, *29*(3), 447–458. https://doi.org/10.1207/s15326942dn2903_4

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., Houts, R., Poulton, R., Roberts, B. W., Ross, S., Sears, M. R., Thomson, W. M., & Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 2693–2698. https://doi.org/10.1073/pnas.1010076108

Moriguchi, Y. (2022). Relationship between cool and hot executive function in young children: A near-infrared spectroscopy study. *Developmental Science*, *25*(2), 1–11. https://doi.org/10.1111/desc.13165

Nussenbaum, K., Scheuplein, M., Phaneuf, C. V., Evans, M. D., & Hartley, C. A. (2020). Moving developmental research online: Comparing in-lab and web-based studies of model-based reinforcement learning. *Collabra: Psychology*, *6*(1), Article 17213. https://doi.org/10.1525/collabra.17213

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). Psychopy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Poon, K. (2018). Hot and cool executive functions in adolescence: Development and contributions to important developmental outcomes. *Frontiers in Psychology*, *8*(January), 1–18. https://doi.org/10.3389/fpsyg.2017.02311

Prencipe, A., Kesek, A., Cohen, J., Lamm, C., Lewis, M. D., & Zelazo, P. D. (2011). Development of hot and cool executive function during the transition to adolescence. *Journal of Experimental Child Psychology*, *108*(3), 621–637. https://doi.org/10.1016/j.jecp.2010.09.008

R Core Team. (2017). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.r-project.org/

Rollins, L., Bertero, E., Hunter, L., & Hills, P. J. (2021). Developmental differences in the visual processing of emotionally ambiguous neutral faces based on perceived valence. *PLoS ONE*, *16*(8), Article e0256109. https://doi.org/10.1371/journal.pone.0256109

Roxburgh, A. D., Hughes, M. E., & Cornwell, B. R. (2019). Threat-induced anxiety weakens inhibitory control. *Biological Psychology*, *144*(April), 99–102. https://doi.org/10.1016/j.biopsycho.2019.03.009

Salvia, E., Aïte, A., Vidal, J., & Borst, G. (2021). Hot and cool response inhibition abilities develop linearly from late childhood to young adulthood. *Cognitive Development*, *58*(March), Article 101039. https://doi.org/10.1016/j.cogdev.2021.101039

Schel, M. A., & Crone, E. A. (2013). Development of response inhibition in the context of relevant versus irrelevant emotions. *Frontiers in Psychology*, *4*, Article 383. https://doi.org/10.3389/fpsyg.2013.00383

Schulz, K. P., Fan, J., Magidina, O., Marks, D. J., Hahn, B., & Halperin, J. M. (2007). Does the emotional go/no-go task really measure behavioral inhibition? Convergence with measures on a non-emotional analog. *Archives of Clinical Neuropsychology*, *22*(2), 151–160. https://doi.org/10.1016/j.acn.2006.12.001

Scott, S. B., Graham-Engeland, J. E., Engeland, C. G., Smyth, J. M., Almeida, D. M., Katz, M. J., Lipton, R. B., Mogle, J. A., Munoz, E., Ram, N., & Sliwinski, M. J. (2015). The effects of stress on cognitive aging, physiology and emotion (ESCAPE) project. *BMC Psychiatry*, *15*(1), Article 146. https://doi.org/10.1186/s12888-015-0497-7

Shalev, N., Bauer, A.-K. R., & Nobre, A. C. (2019). The tempos of performance. *Current Opinion in Psychology*, *29*, 254–260. https://doi.org/10.1016/j.copsyc.2019.06.003

Siegler, R. S. (1994). Cognitive variability: A key to understanding cognitive development. *Current Directions in Psychological Science*, *3*(1), 1–5. https://doi.org/10.1111/1467-8721.ep10769817

Somerville, L. H., Hare, T., & Casey, B. J. (2011). Frontostriatal maturation predicts cognitive control failure to appetitive cues in adolescents. *Journal of Cognitive Neuroscience*, *23*(9), 2123–2134. https://doi.org/10.1162/jocn.2010.21572

Somerville, L. H., Jones, R. M., Ruberry, E. J., Dyke, J. P., Glover, G., & Casey, B. J. (2013). The medial prefrontal cortex and the emergence of self-conscious emotion in adolescence. *Psychological Science*, *24*(8), 1554–1562. https://doi.org/10.1177/0956797613475633

Tottenham, N., Hare, T. A., & Casey, B. J. (2011). Behavioral assessment of emotion discrimination, emotion regulation, and cognitive control in childhood, adolescence, and adulthood. *Frontiers in Psychology*, *2*(March), 1–9. https://doi.org/10.3389/fpsyg.2011.00039

van der Molen, M. W. (2000). Developmental changes in inhibitory processing: Evidence from psychophysiological measures. *Biological Psychology*, *54*(1–3), 207–239. https://doi.org/10.1016/S0301-0511(00)00057-0

Verbruggen, F., Aron, A. R., Band, G. P. H., Beste, C., Bissett, P. G., Brockett, A. T., Brown, J. W., Chamberlain, S. R., Chambers, C. D., Colonius, H., Colzato, L. S., Corneil, B. D., Coxon, J. P., Dupuis, A., Eagle, D. M., Garavan, H., Greenhouse, I., Heathcote, A., Huster, R. J., … Boehler, C. N. (2019). A consensus guide to capturing the ability to inhibit actions and impulsive behaviors in the stop-signal task. *eLife*, *8*, Article e46323. https://doi.org/10.7554/eLife.46323

Verbruggen, F., & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Sciences*, *12*(11), 418–424. https://doi.org/10.1016/j.tics.2008.07.005

West, R., Murphy, K. J., Armilio, M. L., Craik, F. I. M., & Stuss, D. T. (2002). Lapses of intention and performance variability reveal age-related increases in fluctuations of executive control. *Brain and Cognition*, *49*(3), 402–419. https://doi.org/10.1006/brcg.2001.1507

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record*, *58*(3), 475–482. https://doi.org/10.1007/BF03395630

Williams, B. R., Hultsch, D. F., Strauss, E. H., Hunter, M. A., & Tannock, R. (2005). Inconsistency in reaction time across the life span. *Neuropsychology*, *19*(1), 88–96. https://doi.org/10.1037/0894-4105.19.1.88

Wolf, L. K., Bazargani, N., Kilford, E. J., Dumontheil, I., & Blakemore, S.-J. (2015). The audience effect in adolescence depends on who's looking over your shoulder. *Journal of Adolescence*, *43*(1), 5–14. https://doi.org/10.1016/j.adolescence.2015.05.003

Zelazo, P. D., & Carlson, S. M. (2012). Hot and cool executive function in childhood and adolescence: Development and plasticity. *Child Development Perspectives*, *6*(4), 354–360. https://doi.org/10.1111/j.1750-8606.2012.00246.x

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