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Differential Influence of Safe Versus Threatening Facial Expressions on Decision-Making during an Inhibitory Control Task in Adolescence and Adulthood

JE Cohen-Gilbert^{1,3}, WDS Killgore^{2,3}, CN White⁴, ZJ Schwab², DJ Crowley^{1,3}, MJ Covell¹, JT Sneider^{1,3}, and MM Silveri^{1,3}

¹Neurodevelopmental Lab, McLean Imaging Center, McLean Hosp, Belmont, MA

²Center for Depression, Anxiety and Stress Research, McLean Hosp, Belmont, MA

³Psychiatry, Harvard Medical School, Boston, MA

⁴Department of Psychology, Syracuse University, Syracuse, NY

Abstract

Social cognition matures dramatically during adolescence and into early adulthood, supported by continued improvements in inhibitory control. During this time, developmental changes in interpreting and responding to social signals such as facial expressions also occur. In the present study, subjects performed a Go No-Go task that required them to respond or inhibit responding based on threat or safety cues present in facial expressions. Subjects (N = 112) were divided into three age groups: adolescent (12–15 years), emerging adult (18–25 years) and adult (26–44 years). Analyses revealed a significant improvement in accuracy on No-Go trials, but not Go trials, during both safe and threat face conditions, with changes evident through early adulthood. In order to better identify the decision-making processes responsible for these changes in inhibitory control, a drift diffusion model (DDM) was fit to the accuracy and reaction time data, generating measures of caution, response bias, nondecision time (encoding + motor response), and drift rate (face processing efficiency). Caution and nondecision time both increased significantly with age while bias towards the Go response decreased. Drift rate analyses revealed significant age-related improvements in the ability to map threat faces to a No-Go response while drift rates on all other trial types were equivalent across age groups. These results suggest both stimulus-independent and stimulus-dependent processes contribute to improvements in inhibitory control in adolescence with processing of negative social cues being specifically impaired by self-regulatory demands. Findings from this novel investigation of emotional responsiveness integrated with inhibitory control may provide useful insights about healthy development that can be applied to better understanding adolescent risk taking behavior and the elevated incidence of related forms of psychopathology during this period of life.

Keywords

Inhibitory control; Adolescence; Emerging adulthood; Drift Diffusion Model; Faces; Threat

Introduction

The successful transition from childhood to adulthood requires the rapid refinement of social cognitive skills (Nelson, Leibenluft, McClure, & Pine, 2005). As adolescents become more independent and progress into a peer-dominated social sphere, it becomes necessary for them to successfully navigate increasingly complex social interactions (Arnett, 1999). Successful negotiation of such exchanges requires the convergence of multiple cognitive skills. One such ability is the capacity to inhibit impulsive responses in order to avoid making socially inappropriate responses or taking maladaptive actions. A second key social cognitive skill is the ability to accurately interpret cues from others, such as those discernable in facial expressions. Given that these cues are often subtle and fleeting, adolescents must learn to rapidly interpret and respond to facial cues while simultaneously regulating their own behavior in order to achieve their goals within social contexts.

Numerous studies to date examining the development of inhibitory control during adolescence have generated substantial evidence that the ability to withhold impulsive or prepotent responses improves progressively during adolescence (Cohen-Gilbert & Thomas, 2013; Hooper, Luciana, Conklin, & Yarger, 2004; Johnstone, Pleffer, Barry, Clarke, & Smith, 2005; Jonkman, 2006; Lamm, Zelazo, & Lewis, 2006; Rubia, et al., 2006). Parallel neuroimaging research has suggested that this improvement in regulatory ability is supported largely by maturation of the prefrontal cortex (PFC) (Casey, Giedd, & Thomas, 2000; Paus, 2005). Such findings include consistent evidence for developmental changes in PFC recruitment during inhibitory control tasks over the course of adolescence (see (Luna, Padmanabhan, & O'Hearn, 2010) for review) and structural changes in the PFC (Giedd, et al., 1999; Gogtay, et al., 2004). However, despite evidence of ongoing PFC development into emerging adulthood (Gogtay, et al., 2004), few studies have extended developmental investigation by comparing inhibitory control between emerging adults and adults. Emerging adulthood is a demographically and subjectively distinct developmental phase from both adolescence and early adulthood, characterized by a shift away from direct parental supervision without acquisition of full adult roles. This period typically involves extensive identity exploration and is associated with elevated risk-taking behaviors relative to adulthood (Arnett, 2000). While largely culturally defined, emerging adulthood also features ongoing neural development in brain regions relevant to both self-regulation and social cognition (Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). There is, however, a dearth of cognitive studies that directly compare emerging adulthood to both adolescent and adult age groups.

Emotional responding and inhibitory control are mutually influential processes. Cognitive control may be used to alter emotion-driven responses, as well as to overcome powerful emotions that can disrupt self-control (Cyders & Smith, 2008). Brain regions critical to supporting these processes include the PFC and the amygdala, which are extensively

interconnected (Ochsner & Gross, 2005). These connections demonstrate marked maturational changes throughout adolescence (Cunningham, Bhattacharyya, & Benes, 2002). Emotional Go No-Go tasks have been used to explore the developing interaction between responses to emotion cues and inhibitory control in adolescence (Cohen-Gilbert & Thomas, 2013; Hare, et al., 2008; Ladouceur, et al., 2006; Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006; Somerville, Hare, & Casey, 2011; Tottenham, Hare, & Casey, 2011). These studies have found evidence of improvements in facial emotion discrimination and inhibitory control across adolescence, with larger age-related improvements in inhibitory control observed when emotional stimuli were presented as compared to neutral stimuli (Tottenham, et al., 2011). Neuroimaging studies using emotional faces as stimuli for Go No-Go tasks have revealed increased amygdala reactivity to faces depicting fearful affect in adolescents relative to children and adults (Hare, et al., 2008). These adolescents also showed slowed responding to fear faces compared to adults, interpreted as a weaker capacity to override an instinctive withdrawal from a negative stimulus (Hare, et al., 2008). In the same subject sample, increased impulsive errors to happy versus calm faces were also evident in adolescents relative to children and adults, a finding interpreted as an inability to withhold approach behaviors to emotionally positive stimuli. This pattern was paralleled by increased recruitment of ventral striatum, a brain area implicated in reward-processing (Somerville, et al., 2011). Together, these studies suggest heightened sensitivity to emotional information during Go No-Go task performance in adolescents relative to other age groups. Thus, the presence of social information in the form of overt emotional facial expressions appears to be particularly disruptive to inhibitory control efforts during adolescence. To date, however, all facial affect Go No-Go tasks used to examine adolescent development have employed highly prototypical examples of basic emotions (e.g. happiness, sadness, fear, anger and neutral). Optimal social functioning in daily life requires the discernment of much subtler cues. The current study aims to explore the impact of less obvious threat and safety cues, present in facial expressions, on inhibitory control across development in adolescence, emerging adulthood and adulthood.

The interpretation of, and responding to, facial expressions of emotion outside the context of an inhibitory control task also continues to develop during adolescence and into emerging adulthood. Evidence suggests that both the ability to discern subtle differences in facial cues and speed of recognition for emotional expressions continue to develop throughout adolescence (McGivern, Andersen, Byrd, Mutter, & Reilly, 2002; Thomas, De Bellis, Graham, & LaBar, 2007). In particular, the ability to distinguish subtle anger cues may remain immature throughout most of adolescence and then improve rapidly in early adulthood while the ability to identify similarly subtle fear cues improves linearly across adolescence (Thomas, et al., 2007). Brain activation in response to viewing facial expressions, as measured by fMRI, has also been found to change during adolescence. In particular, amygdala activity in response to viewing fearful faces was elevated in adolescents relative to adults (Guyer, et al., 2008; Monk, et al., 2003) and decreased with age across adolescence (Killgore, Oki, & Yurgelun-Todd, 2001), while PFC activity increased (Yurgelun-Todd & Killgore, 2006). Thus, processing of negative emotional facial expressions appears to shift somewhat from emotion-processing areas and to regulatory brain regions during adolescence, potentially affecting the ability to recognize and respond

to emotional cues. In addition to these developmental changes in processing emotional faces, sex differences in brain activity in response to facial affect have been reported in adolescent populations (Killgore, et al., 2001; Killgore & Yurgelun-Todd, 2004), as well as sex differences in performance of an emotional Go No-Go task (Tottenham, et al., 2011). Therefore, both age and sex may impact inhibitory control during the processing of facial cues, though the interactions between these two factors are not yet well understood.

The objective of the current study was to evaluate developmental changes in adolescence and emerging adulthood in performance of a Go No-Go task that requires fast, on-line processing of subtle computer-generated facial cues indicating threat or safety (Oosterhof & Todorov, 2008) at the same time as inhibitory demands are being placed on the subject. In this way, this protocol taps into inhibitory control, as well as the ability to discriminate between safe and threatening faces. Given that a number of other factors, such as cautiousness of responding (i.e., their speed/accuracy tradeoff), may impact accuracy and reaction time measures, a drift-diffusion model (DDM, (Ratcliff, 1978) of simple decisions was fitted to the behavioral data. This model uses accuracy and response time data to extract values for response caution, response bias, nondecision time (time needed to encode the stimulus and execute a motor response), and stimulus processing for each individual. This type of model-based approach has been successfully applied to examine group differences in developmental studies (Ratcliff, Love, Thompson, & Opfer, 2012), aging studies (Starns & Ratcliff, 2012) and psychopathology studies (White, Ratcliff, Vasey, & McKoon, 2010a, 2010b).

Given that both inhibitory control and social information processing are actively developing during adolescence, it was hypothesized that accuracy on No-Go trials would improve with age and that the impact, or disruptiveness, of emotionally salient threat stimuli on accuracy would be greatest in the adolescent group. Response caution was also predicted to increase with age, while the ability to correctly discriminate between the two face types was also predicted to improve between adolescence and adulthood.

Methods

Participants

The sample consisted of 112 participants, subdivided into three age groups: 1) 33 adolescents (ADO, 16 male), mean age = 13.6 ± 0.9 years, age range = 12–15 years; 2) 38 emerging adults (EA, 17 male), mean age = 22.0 ± 1.8 years, age range 18–25 years; and 3) 41 adults (ADU, 21 male), mean age = 35.0 ± 6.3 years, age range = 26–46 years. Ages 18–25 years were chosen to represent emerging adulthood based on demographic data (Arnett, 2000) and neurodevelopmental findings (Sowell, et al., 1999). The racial composition of the sample was 70% Caucasian, 16% African American, 9% Asian, and 6% multiracial/other. Four percent of the sample identified as Hispanic. Participants were recruited from the surrounding community via internet postings and flyers. All potential subjects were screened via telephone interview. Exclusion criteria included history of severe medical conditions, head injury, loss of consciousness (> 30 min), brain tumors, seizures, other neurologic conditions, sensory deficits, symptoms consistent with Axis I psychopathology, or drug or alcohol dependence. Additionally, potential participants were excluded for current or recent

use of any psychoactive medications, illicit substances, or excessive alcohol intake. One young adult female was a statistical outlier (overall accuracy > 3 SD below the mean) and was therefore excluded from all analyses. Written informed consent was obtained prior to enrollment from all adult participants and from parents of adolescent participants. Adolescent participants provided written informed assent. All participants were compensated for their time. The research protocol was approved by the McLean Hospital Institutional Review Board.

Go No-Go Paradigm

Subjects performed a computer-based social threat Go No-Go task, presented using E-Prime (Psychology Software Tools, Inc., Sharpsburg, PA, USA). The task consisted of two blocks of 180 trials (25% No-Go trials). Within each trial an image depicting a ‘safe’ or ‘threat’ face was displayed for 100 milliseconds (msec) followed by an intertrial interval of 1400 msec during which the subject could respond. In two separate blocks, subjects were instructed to either press the spacebar (Go) when safe faces were presented and refrain from pressing (No-Go) when threat faces were presented (condition A, see Figure 1a), or press the spacebar (Go) when threat faces were presented and refrain (No-Go) when safe faces were presented (condition B, see Figure 1b). Each block lasted 4.5 minutes. Due to the higher number of Go trials presented within each block, subjects developed a prepotent tendency to press and needed to actively inhibit pressing during No-Go trials. Percent accuracy on Go and No-Go trials and response time on correct Go trials were recorded. While task condition order was not fully counterbalanced, a subsample of individuals completed the task in the inverse order (condition B followed by A) and revealed no significant differences in performance due to order of task condition.

Safe and threatening face stimuli were selected from stimulus sets developed by Oosterhof and Todorov (Oosterhof & Todorov, 2008) using the Facegen Modeller program (Singular Inversions Inc., Toronto, Canada, <http://facegen.com>, Version 3.1.). The selected face stimuli consisted of 45 different male Caucasian faces. Two different versions of these 45 faces were selected: one morphed in each direction along the ‘trustworthiness’ vector by three standard deviations. Across the full task (conditions A and B), each safe or threat face was presented once as a No-Go stimulus and three times as a Go stimulus.

Drift Diffusion Model

A DDM (Ratcliff, 1978; Ratcliff & Smith, 2004) was fit to each participant’s behavioral data to extract components of psychological processing. The model assumes that noisy evidence is accumulated over time until a boundary is reached, signaling a commitment to that response (Figure 2). The decision time is calculated as the time taken to reach a boundary, and the overall response time is equal to the decision time plus a value of nondecision time that accounts for the duration of other processes like encoding and motor execution. Previous work shows that the DDM can successfully account for No-Go data by assuming that there is an implicit boundary representing the No-Go option, meaning the individual commits to withhold the response once that boundary is reached (Gomez, Ratcliff, & Perea, 2007).

The primary components of the model are the boundary separation, starting point, drift rate, and nondecision time. The boundary separation provides an index of response caution (the speed/accuracy tradeoff); wide boundaries indicate a cautious response style that favors accuracy over speed. The starting point, z , provides an index of response bias. In a Go No-Go task where Go trials are much more probable than No-Go trials, people are generally biased toward the Go response and movement towards the No-Go boundary requires active suppression of the Go response (Gomez, et al., 2007). This is reflected by a shift in the starting point toward the Go boundary, meaning less evidence is required for that response. The nondecision time (Ter) provides an index of the duration of nondecision processes, including encoding of the stimulus and execution of the motor response. Finally, the drift rate (v) provides an index of how readily a person can extract evidence from the presented stimulus; higher absolute values of drift rate indicate strong evidence and lead to fast and accurate responses. In this present task, drift rate indexes how effectively subjects map threat and safe faces onto the correct responses. This involves not only discriminating threat from safe faces, but also relating those faces to either response execution (Go trials) or inhibition (No-Go trials). Four drift rates were calculated based on the stimulus conditions; safe face Go trials, safe face No-Go trials, threat face Go trials, and threat face No-Go trials.

The DDM was designed to account for the full observable data from all trials. This includes accuracy and the distribution of RTs for Go trials, as well as the percentage of commission errors and their RTs on No-Go trials. The model was fit to each participant's data separately for the two sessions, estimating for each session a value of response caution, drift rate for safe faces, drift rate for threat faces, response bias, and nondecision time. A parameter for across-trial variability in starting point was added to capture trial-by-trial fluctuations in response bias, allowing the model to account for extremely fast responses (i.e., guesses). Although this parameter helps the model fit the data, it is not generally used for inference and thus is not discussed further. The fitting process used the χ^2 -minimization technique (Ratcliff & Tuerlinckx, 2002) based on the quantiles of the RT distribution. For correct Go responses, the standard quantiles of the RT distribution (.1, .3, .5, .7, .9) were used to compare against the predicted data from the model. The .1 quantile is the time at which 10% of responses have occurred, the .3 quantile is the time at which 30% of response have occurred, and so on (Figure 4). These RT quantiles were used with the proportion of each trial type (correct or omission) to provide the χ^2 fit index, which was minimized by a SIMPLEX routine.

Estimating the RT quantiles and the subsequent DDM parameters is facilitated by the collection of a very large number of trials. The participants in this study had over 100 observations for each Go condition, which is fewer than previous applications of the model, but enough to produce stable estimates of the distribution of RTs for each condition. Nonetheless, the estimation of the DDM parameters may have more variability because of the relatively low number of observations to constrain the model. This is a general concern for the application of DDMs in situations where data collection is limited by a variety of factors. However, there is no reason to expect that this limitation differentially affects the age groups in this study, thus the differences among the groups should not be confounded.

Statistical Analyses

Accuracy on No-Go trials was analyzed as the principal index of inhibitory control while accuracy on Go trials was used to measure sustained attention to the task. Reaction time on correct Go trials was used to examine total encoding, decision-making, and response speed. Measures of caution (boundary separation), response bias (z), nondecision time (Ter), and drift rate (v), were derived from the DDM. Each outcome variable was analyzed using analyses of variance (ANOVAs) including Age (ADO, EA, ADU) and Sex (male, female) as between-subject factors. In cases where separate measures were computed for Safe and Threat trials and/or Go and No-Go trials, Face Type and Trial Type were included as within-subject factors. All *post hoc* t-tests were two-tailed and corrected for multiple comparisons using Tukey HSD. All ANOVAs and *post hoc* tests were conducted using PASW Statistics 18.0 (SPSS Inc. Released 2010. PASW Statistics for Mac, Version 18.0. Chicago: SPSS Inc.)

Results

Accuracy and Reaction Time Data

Go and No-Go accuracy—A $3(\text{Age}) \times 2(\text{Sex}) \times 2(\text{Face Type}) \times 2(\text{Trial Type: Go vs. No-Go})$ mixed-model ANOVA revealed main effects of Age, $F(2, 108) = 11.72, p < .001, \eta^2 = .178$, Face Type, $F(1, 108) = 35.78, p < .001, \eta^2 = .249$, and Trial Type, $F(1, 108) = 83.35, p < .001, \eta^2 = .436$, as well as significant Age $\times$ Trial Type, $F(2, 108) = 31.93, p < .001, \eta^2 = .372$, and Face Type $\times$ Trial Type, $F(1, 108) = 9.08, p = .003, \eta^2 = .078$, interactions. No other main effects or interactions were statistically significant.

Post hoc analysis of the Age $\times$ Trial Type interaction was conducted using two one-way ANOVAs ($\alpha = .025$ to correct for multiple comparisons) examining the effect of Age separately for accuracy on Go trials and on No-Go trials. While the main effect of Age was not significant, $p = .14$, for Go trial accuracy, a significant main effect of Age was evident for No-Go trial accuracy $F(2, 108) = 30.67, p < .001, \eta^2 = .362$. Significantly lower No-Go accuracy was observed in ADO compared to EA, $p = .001$, and ADU, $p < .001$, and significantly lower No-Go accuracy was observed in EA compared to ADU, $p = .019$ (Figure 3).

The Face Type $\times$ Trial Type interaction was followed up via two paired-samples t-tests comparing accuracy on Safe versus Threat faces separately for Go and No-Go trials. Results showed a significant effect of Face Type on both Go, $t(110) = 7.16, p < .001$, and No-Go trials, $t(110) = 3.88, p < .001$, with accuracy on Safe trials being higher in both cases. The observed interaction may be explained by a larger effect of face type on Go trials, (Safe: Mean = 93.1%, SD = 10.7%; Threat: Mean = 82.2%, SD = 16.7%) than on No-Go trials (Safe: Mean = 77.4%, SD = 19.3%; Threat: Mean = 70.9%, SD = 21.2%).

Reaction time: correct Go trials—Reaction times were analyzed via a $3(\text{Age}) \times 2(\text{Sex}) \times 2(\text{Face Type})$ mixed-model repeated measures ANOVA. This analysis revealed significant main effects of Age, $F(2, 108) = 3.91, p = .028$, and Face Type, $F(1, 108) = 21.33, p < .001$. No other significant effects were found. *Post hoc* comparisons between each of the three age

groups revealed significantly longer reaction times in ADU relative to ADO, $p = .029$, and a trend towards longer reaction times in ADU relative to the EA, $p = .09$. No significant difference in reaction time was found between ADO and EA. The main effect of Face Type was due to longer reaction times on Threat versus Safe trials. Reaction time data is summarized in Table 1.

Application of the Drift Diffusion Model

The fit quality of the DDM was assessed quantitatively by examining best-fitting χ^2 values and qualitatively by plotting the observed data against predicted data from the model parameters. The χ^2 (ADO: Mean = 187.17, SD = 250.85; EA: Mean = 81.06, SD = 67.16; ADU: Mean = 66.28, SD = 34.34) values were found to be in line with results from similar studies (e.g. White et al., 2010a,b), and the predicted data were highly similar to the observed data (Figure 4). Together these findings suggest that the DDM captured the behavioral data well, allowing confidence in the resulting parameter values.

Diffusion Model Parameters

Response caution—A 3(Age) $\times$ 2(Sex) $\times$ 2(Face Type) mixed-model ANOVA revealed a main effect of Age, $F(2, 105) = 4.02$, $p = .021$, $\eta^2 = .071$, on response caution. No other significant effects were found for this variable. *Post hoc* comparisons between each of the three age groups revealed a significantly lower caution for ADO compared to ADU, $p = .022$, while neither of these age groups differed significantly from EA. Values for response caution, response bias and nondecision time are summarized in Table 1.

Response bias—A mixed model ANOVA including Age and Sex and between-subject factors and Face Type as a within subject factor revealed only a main effect of Age on response bias, $F(2, 105) = 3.43$, $p = .036$, $\eta^2 = .061$. *Post hoc* comparisons showed a significant difference in response bias between ADO and ADU, $p = .049$, but no significant differences between either of these age groups and EA. Overall ADO were more biased toward the Go response than ADU, which reduces the likelihood of successful inhibition on No-Go trials.

Nondecision time—A univariate ANOVA including Age and Sex as fixed factors revealed a main effect of Age on nondecision time, $F(1, 105) = 12.37$, $p < .001$, $\eta^2 = .191$. No other significant effects were found. *Post hoc* comparisons between age groups revealed significantly shorter nondecision times in ADO compared to EA, $p = .024$, and ADU, $p < .001$, and a trend towards shorter nondecision times in EA relative to the ADU, $p = .056$.

Drift rate—Higher values of drift rate indicate a better ability to translate the stimulus face into the appropriate response (Go or No-Go). A 3(Age) $\times$ 2(Sex) $\times$ 2(Face Type) $\times$ 2(Trial Type: Go vs. No-Go) mixed-model ANOVA revealed significant main effects of Face Type $F(1, 105) = 71.64$, $p < .001$, $\eta^2 = .406$ and Trial Type $F(1, 105) = 56.30$, $p < .001$, $\eta^2 = .349$, as well as significant Face Type $\times$ Trial Type, $F(1, 105) = 12.81$, $p = .001$, $\eta^2 = .109$, and Age $\times$ Face Type $\times$ Trial Type, $F(2, 105) = 5.80$, $p = .004$, $\eta^2 = .099$, interactions. A trend-level effect was also found for a Sex $\times$ Face Type interaction, $F(1, 105) = 3.77$, $p = .055$, $\eta^2 = .035$.

Post hoc analyses of the Age $\times$ Face Type $\times$ Trial Type interaction were conducted first by using two mixed-model ANOVAs ($\alpha = .025$) examining the effects of Age and Face Type separately on Go trials and on No-Go trials. Drift rates showed main effects of Face Type (Go trials, $F(1, 105) = 16.80, p < .001, \eta^2 = .138$; No-Go trials $F(1, 105) = 68.28, p < .001, \eta^2 = .394$) with drift rates being greater for safe faces than for threat faces on both Go and No-Go trials. However, only the No-Go trial analysis also revealed a significant main effect of Age, $F(2, 105) = 3.77, p = .026, \eta^2 = .067$, and a significant Age $\times$ Face Type interaction $F(2, 105) = 4.70, p = .011, \eta^2 = .082$. Examining No-Go trials only, separate one-way ANOVAs were used to assess the impact of Age on drift rate for safe face trials versus threat face trials. While no effect of Age was observed on safe trials, $p = .755$, a significant effect of Age was found for threat trials, $F(2, 108) = 5.82, p = .004, \eta^2 = .097$. For No-Go threat trials, *post hoc* t-tests contrasting each of the three age groups revealed a significant difference between ADO and ADU, $p = .003$, but no significant differences in drift rate between EA and the other two age groups. In summary, the ability to map safe face stimuli onto a No-Go response did not differ as a function of age while the ability to map threat faces to a No-Go response improved across the sampled age range. Drift rate findings are summarized in Figure 5.

Discussion

Consistent with previous reports, adolescents in the present study demonstrated worse inhibitory control than emerging adults and adults, reflected by higher error rates on No-Go trials (Hooper, et al., 2004; Johnstone, et al., 2005; Jonkman, 2006; Lamm, et al., 2006; Rubia, et al., 2006; Marisa M Silveri, et al., 2013). While few studies have directly examined the possibility of ongoing changes in inhibitory control that extend into emerging adulthood, the current study revealed significant improvements in response inhibition between the emerging adult group (mean age = 22 years) and the adult group (mean age = 35 years). These findings are in contrast with the only existing investigation of emerging adults, in which no significant performance differences were observed between 20 year old and 36 year old subjects on a non-emotional Go No-Go task (Johnstone, et al., 2005). However, the current findings suggest that developmental changes in inhibitory capacity do extend into adulthood when tasks are sufficiently complex, such as when simultaneous emotional information processing and response inhibition are required.

The current adult group displayed improved inhibitory control relative to both groups of younger subjects, as well as slower reaction times on Go trials, suggesting that this group sacrificed response speed in order to commit fewer impulsive errors. This interpretation is supported by the age-related increases found on the response caution measure derived from the DDM. Changes in speed accuracy trade-off, however, do not solely account for the observed developmental changes in impulsivity. Age-related differences in response bias and nondecision time also were found and likely also to contribute to the reduction of impulsive errors with age. In other words, multiple developmental changes in cognitive processing contribute to reductions in impulsivity between adolescence and adulthood: a shift in speed-accuracy trade-off, a reduction in the bias toward Go responding, and the use of longer intervals to encode the stimulus and execute the button press. Notably, significant changes on the majority of these metrics were not observed between the adolescent and

emerging adult groups, or between the emerging adult and adult groups, suggesting that these cognitive skills develop very gradually and continue to mature well beyond the teen years. In contrast with the current findings, nondecision times have been previously reported to decrease with age between adolescence and early adulthood on a number discrimination task (Ratcliff, et al., 2012). Given the demands of the current task, however, adults may respond in part by increasing encoding time for the more complex stimuli or slowing motor responses to account for the need to periodically override the prepotent Go response.

The presence of a threat stimulus negatively impacted accuracy on both Go and No-Go trials, while increasing reaction times on Go trials, indicating that a threat stimulus disrupted task performance across all age groups in this study. The absence of any interaction effects between face type and age group on these measures suggests that, contrary to our hypothesis and previous findings (Hare, et al., 2008), the presence of a social threat stimulus was not more disruptive than a safe stimulus in adolescents relative to the older participants. The integration of facial emotion recognition and inhibitory control into a single task provides a useful model of social cognition. However, because of this integration, this task confounds the ability to interpret facial expressions with the impact of emotional content on inhibitory control, making accuracy scores on inhibitory trials difficult to interpret. That is, accurate responding on NoGo trials depends both on the ability to correctly identify the face stimulus as either safe or threatening, and on the ability to withhold a prepotent response to an emotional stimulus. Thus, errors could result either from inaccurate identification of the stimulus, or from failed response inhibition. By fitting a DDM to the accuracy and reaction time data, this study succeeded in isolating specific aspects of the decision-making process that mature between adolescence and adulthood.

The DDM measures provide important insight into the development of cognitive skills underlying impulse control in response to threatening and safe social cues. Importantly, drift rate provides a measure of how readily a participant can extract evidence from a stimulus towards a correct response. In other words, drift rate measures how readily the safe and threat cues were mapped onto a correct response: pressing (Go trials), or refraining from pressing (NoGo trials). This measure revealed an interaction between trial type, face type and age group that was not evident when accuracy or reaction time data were examined alone. Specifically, while drift rates on both safe and threat Go trials and on safe No-Go trials appeared to be at adult levels throughout the age range studied, drift rate on threat No-Go trials was lower in adolescents versus adults. This suggests that adolescents were less able to map the negative social cue onto the correct withholding response. Thus, while increased impulsive errors were observed in the younger age groups for safe and threat No-Go trials, these errors resulted from different components of the decision-making process. Reduced caution, greater Go bias, and shorter nondecision times, resulted in more errors on safe trials in the adolescent group, with an additional factor affecting performance on threat No-Go trials: the ability to map a threatening cue onto a successful inhibitory response. This finding is congruent with previous studies that have reported a more protracted development of executive functions on motivationally or emotionally salient tasks relative to tasks with a minimal emotional component (Prencipe, et al., 2010; Tottenham, et al., 2011). Likewise, Go No-Go performance in the context of negative emotional distractors has been found to lag behind developmental improvements in other emotional contexts (Cohen-Gilbert &

Thomas, 2013). An argument could be made that adolescents have more difficulty mapping threat onto inaction as opposed to action due to an evolutionary bias towards sensation seeking and threat tolerance in order to enable migration away from the family unit at puberty, thus reducing chances of inbreeding (Spear, 2000; Spear, 2007). A bias to act rather than freeze in response to threat may also help juveniles compete for resources and mates. These possibilities are, however, purely speculative.

It is surprising that the present study did not show any significant sex differences, as sex differences in emotional processing have often been reported among adolescents (Killgore, et al., 2001; Killgore & Yurgelun-Todd, 2004) and adults (Killgore & Yurgelun-Todd, 2001). The stimuli in the present study, however, were “facial identities” differing in perceived trustworthiness, not emotional expressions per se. Thus, the influence of the sex may be specific to responding to explicit emotional rather than social-threat aspects of face processing. Additionally, the present study employed a homogeneous set of facial identities, all with features consistent with those of Caucasian males, which reduced the number of potential complex interactions and focused the analysis on the primary dimensions of interest. It is possible, however, that including female stimuli and identities consistent with other racial backgrounds might have yielded additional interaction effects, which should be explored in future research.

A strength of this study was the inclusion of relatively large sample sizes within each age group, however, it is worth noting that the adolescent group was restricted to a three-year age span, whereas the emerging adult group spanned seven years and the adult group spanned twenty years. This design assumes a slowing rate of change in cognitive skill with age across the studied range. This assumption, however, is not without basis as the rapid development of cognitive control occurring in childhood and adolescence begins to plateau as individuals reach adulthood (Luna, Garver, Urban, Lazar, & Sweeney, 2004; Luna, et al., 2010).

The shift from a parent-centered to a peer-centered social environment places novel cognitive demands upon the developing adolescent. The absence of supervision by a caregiver increases the demand for self-regulation, as actions and decisions become increasingly independently determined. The complexity of social relationships also increases as friendships and romantic relationships become more influential sources of emotional support, self-conception, and self-esteem. Understanding the thoughts and emotions of others becomes increasingly necessary for the successful maintenance of these relationships. Thus, both inhibitory control and accurate recognition of social cues are critical skills for developing adolescent social functioning. The current study provides further evidence that these skill sets continue to improve across adolescence, and that response inhibition continues to develop during emerging adulthood, albeit potentially at the cost of response speed. Moreover, results of the current study suggest a specific impairment in translating negative social stimuli into a non-response, a finding with clear implications for adolescents who frequently may need to regulate their actions during stressful or negative interactions. It is not yet clear whether the observed developmental improvements in socially-relevant cognitive skills are driven by continued maturation in brain areas such as the PFC, or if the increasingly complex social demands placed upon the individual during this period promote

the continued development of relevant neural networks. It is likely that these processes are mutually influential. Whether biologically or environmentally driven, acquisition of social skills is critical to the successful navigation of adolescence.

Both reduced cognitive control and heightened responding to emotional cues have been associated with elevated risk for multiple forms of psychopathology in adolescents (Killgore & Yurgelun-Todd, 2005, 2006; Ladouceur, et al., 2006; M. M. Silveri, Rogowska, McCaffrey, & Yurgelun-Todd, 2011) and other age groups (Leppänen, 2006; Silbersweig, et al., 2007; Wessa, et al., 2007). To the extent that adolescent mental health is closely tied to successful navigation of social interactions with parents, teachers and peers (Parker, Rubin, Erath, Wojslawowicz, & Buskirk, 2006; Spear, 2000), development of top-down control networks to regulate both behavior and emotional responding is critical to healthy development during adolescence and into emerging adulthood. Thus, the social-threat Go No-Go task implemented in this study may be readily used to explore questions of risk for psychopathology during development through the exploration of individual differences in task performance.

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Figure 1. Sample task stimuli. a) In condition A, participants were instructed to press (Go) for safe faces and withhold pressing (No-Go) for threatening faces. b) In condition B, participants were instructed to press (Go) for threatening faces and withhold pressing (No-Go) for safe faces.

Figure 2.

A schematic of the DDM. After the stimulus is encoded, noisy evidence is sampled over time until one of the boundaries is reached (see text for details). Measures obtained from the model include boundary separation, response bias (z), nonddecision time (T_{er}), and drift rate (v).

Figure 3.

Accuracy across age groups. On Go trials, accuracy did not change significantly with age and was consistently higher on Safe versus Threat trials. No-Go accuracy increased significantly with age between each age group (ADO = adolescent, EA = emerging adult, ADU = adult) and was also significantly higher on Safe versus Threat trials.

Figure 4.

Fit quality from the DDM. Predicted values from the best fitting DDM parameters are plotted against the observed values for the proportion of correct Go responses (upper left), the RT quantiles for Go responses (lower), and the median RT for commission errors (CE, upper right). Each point represents a participant. The correspondence between observed and predicted values shows that the model captured the data well.

Figure 5.

Drift rate across age groups. On both Safe and Threat Go trials and Safe No-Go Trials, drift rate did not change significantly with age. Drift rate on Threat No-Go trials increased significantly with age between the adolescent (ADO) and adult (ADU) groups, while the emerging adult (EA) group did not differ significantly from either the older or the younger age group.

Table 1

Reaction Time and DDM measures: Mean(SD)

Measure	Face Type	ADO	EA	ADU
Response Time (msec)	Safe	467.6(76.3)	462.4(65.3)	504.3(90.0)
	Threat	495.4(91.9)	487.0(79.4)	534.1(84.7)
Response Caution	Safe	0.126(0.02)	0.128(0.02)	0.130(0.02)
	Threat	0.127(0.02)	0.129(0.02)	0.139(0.02)
Response Bias	Safe	0.420(0.07)	0.426(0.06)	0.427(0.07)
	Threat	0.312(0.09)	0.331(0.10)	0.360(0.07)
Nondecision time	All	0.207(0.09)	0.254(0.06)	0.292(0.08)