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The development of inhibitory control in adolescence and prospective relations with delinquency

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ABSTRACT

Introduction: Despite the central role of inhibitory control in models of adolescent development, few studies have examined the longitudinal development of inhibitory control *within* adolescence and its prospective association with maladaptive outcomes. The current study evaluated: 1) growth in inhibitory control from early- to middle-adolescence, and 2) the relation between inhibitory control and later delinquency.
Methods: Participants included 387 parent-child dyads (11–13 years old at Wave 1; 55% female; USA). Across three annual assessments, teens completed the Stop Signal Task (SST), and parents completed the Inhibitory Control subscale of the Early Adolescent Temperament Questionnaire-Revised. Teens self-reported their delinquent behaviors in early (*M*age = 12.1) and middle adolescence (*M*age = 14.1) and emerging adulthood (*M*age = 18.2).
Results: Latent growth curve models indicated that SST performance improved curvilinearly from early to middle adolescence (ages 11–15), with growth slowing around middle adolescence. However, no growth in parent-reported inhibitory control was observed. Lower task-based and parent-reported inhibitory control in early adolescence predicted greater increases in delinquency from middle adolescence to emerging adulthood. However, rate of growth in task-based inhibitory control was unrelated to later delinquency.
Conclusions: This longitudinal study provides a novel examination of the development of inhibitory control across early and middle adolescence. Results suggest that the degree to which inhibitory control confers risk for later delinquency may be captured in early adolescence, consistent with neurodevelopmental accounts of delinquency risk. Differences across assessment tools also highlight the need for careful measurement considerations in future work, as task-based measures may be better suited to capture within-person changes over time.

1. Introduction

Inhibitory control is critical for engaging in adaptive, goal-directed behavior. Successful inhibition involves suppressing a dominant or prepotent response in order to execute a subdominant but adaptive response (Barkley, 1997). Poor inhibitory control

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consistently exhibits cross-sectional associations with externalizing behavior problems, including Oppositional Defiant Disorder, substance use disorders (Lipszyc & Schachar, 2010; Wright, Lipszyc, Dupuis, Thayapararajah, & Schachar, 2014), and antisocial behavior (Oosterlaan, Logan, & Sergeant, 1998). Most research on the development of inhibitory control has focused on the childhood period (e.g., Posner & Rothbart, 2000), even though inhibitory control continues to develop throughout adolescence. Protracted development of self-regulatory systems is considered a key mechanism contributing to the increase in risky and delinquent behaviors often observed during adolescence (Casey, Getz, & Galvan, 2008; Crone & Dahl, 2012; Steinberg, 2008). Despite the importance of inhibitory control in models of adolescent development, studies within the adolescent period are often cross-sectional; longitudinal studies generally have not evaluated the pattern of change nor the extent of individual differences in change over time, precluding a fine-grained analysis of development. The current longitudinal study addresses this gap in the literature and advances the field's understanding of inhibitory control by 1) examining growth in inhibitory control from early to middle adolescence and 2) testing the degree to which initial levels of inhibitory control at age 11, as well as growth in inhibitory control from ages 11 to 15, relates to later delinquent behavior.

1.1. *A framework for inhibitory control*

Terms such as inhibitory control, self-regulation, cognitive control, impulsivity, etc. are often used interchangeably to describe the same phenomenon or construct. In the current study, we use the framework of Nigg (2017) to distinguish inhibitory control from other related processes. Nigg outlines self-regulation as a broad, domain-general ability to flexibly and adaptively modulate one's own behavior and internal states. Inhibitory control (termed response inhibition in Nigg's framework) involves preventing a response or stopping an ongoing response and is considered a building block for more complex cognitive functions.

It is important to distinguish impulsivity from inhibitory control, as both involve regulation of behavior. Making this distinction is complicated by the myriad meanings “impulsivity” has taken (e.g., Smith et al., 2007). One of the key distinguishing factors is that impulsivity entails disinhibition in the context of valenced stimuli and involves the prioritization of immediate over delayed consequences. Thus, the term “impulsivity” takes into account both top-down control and the motivational context of the situation. In contrast, inhibitory control does not explicitly consider motivational context and reflects the capacity to prevent a response or stop on ongoing response.

1.2. *Measurement of inhibitory control*

Behavioral assessment of inhibitory control tends to focus on laboratory task performance. Common paradigms include the Stop Signal Task (SST), the go/no-go, and the antisaccade task. The SST was developed by Logan, Cowan, and Davis (1984) and is one of the most widely-used and theoretically-grounded inhibition paradigms. The SST involves responding to a series of visually-presented stimuli; infrequently, a tone (the stop signal) is presented after the stimulus, indicating that the participant should withhold responding for the stimulus. In the go/no-go, participants are instructed to respond to particular stimuli (e.g., letter “X” but not “O”). The primary difference between the go/no-go and SST is that the cue to withhold responding in the SST is presented *after* the “go” stimulus, thus requiring cancellation of a “go” response that has already been initiated (Logan et al., 1984). The antisaccade is an oculomotor (eye movement) paradigm in which participants are instructed to make a saccade in the direction opposite of the presented stimulus (i.e., if a stimulus is presented to the left, the participant is supposed to look to the right); the number of errors made by looking in the same instead of opposite direction is considered the indicator of inhibitory control. Factor analytic work suggests that the SST loads more strongly than other common-used tasks on a latent inhibition factor, (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), suggesting that it is a strong indicator of inhibitory control.

Parent-report and child self-report questionnaires are also used to evaluate inhibitory control and related constructs, although far fewer questionnaire measures exist to evaluate adolescent inhibitory control because most measures that have been used in adolescence focus on *impulsivity* (Harden & Tucker-Drob, 2011; Lydon-Staley & Geier, 2018; Steinberg et al., 2008), which, as discussed above, is problematic as a measure of inhibitory control. A common questionnaire measure of inhibitory control is from the Early Adolescent Temperament Questionnaire (EATQ; Capaldi & Rothbart, 1992). The inhibitory control subscale of the EATQ is a facet of the broader effortful control scale, which involves the ability to flexibly regulate attention and behavior. The inhibitory control subscale focuses specifically on the ability to inhibit a strong or dominant response. Though this definition is similar to what is supposedly assessed with task-based measurement, one critical difference is that questionnaire measures typically ask about one's ability to inhibit behavior in a variety of contexts that arise in children's lives when it is prudent to inhibit. As such, the items reflect the capacity to inhibit in contexts in which there is typically some motivation to respond. In this way, it overlaps somewhat with questionnaire measures of impulsivity, except that impulsivity measures often include the notion of “rash” responding (Dawe, Gullo & Luxton, 2004). This is in contrast to the SSRT, which is administered in a “cold” cognitive context where approach/avoidance motivation and emotion regulation is less relevant. In the current study, we utilized the SST for task-based inhibitory control and the inhibitory control subscale of the EATQ-R for questionnaire-based inhibitory control.

1.3. *Development of inhibitory control*

Prominent developmental neuroscience models of adolescent risk behavior (e.g., Dual Systems Models, Maturational Imbalance Model) posit that cognitive control processes continue to develop throughout adolescence and emerging adulthood, with cognitive control not fully maturing until approximately the mid-20s (Casey, 2015; Casey et al., 2008; Crone & Dahl, 2012; Shaw et al., 2008;

Steinberg, 2008). The relative immaturity of the cognitive control system is thought to confer risk for a host of maladaptive adolescent outcomes. Despite the prominence of these models, surprisingly few longitudinal studies have evaluated the development of inhibitory control across adolescence. Most of the support for the models comes from cross-sectional studies, even though the ability of cross-sectional designs to inform development is limited, and erroneous inferences can be made when attempting to understand developmental changes with cross-sectional data (see McCormick, Qu, & Telzer, 2017).

Cross-sectional age comparisons provide some support that adolescents exhibit levels of inhibitory control in between those of children and adults (e.g., Klein & Foerster, 2001; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Padmanabhan, Geier, Ordaz, Teslovich, & Luna, 2011; Velanoza, Wheeler, & Luna, 2009; Williams, Ponesse, Schachar, Logan, & Tannock, 1999), with some evidence of age-related improvements in inhibitory control within the adolescent period (Malagoli & Usai, 2018). For example, Williams et al. (1999) examined age-related differences in performance on the Stop Signal Task and found that adolescents (ages 13–17) exhibited better inhibitory control (i.e., lower stop signal reaction time, SSRT) than children, but similar levels to participants in the emerging adult group.

Cross-sectional evaluations of other cognitive control processes suggest potential curvilinear changes in planning and working memory, dependent on task difficulty. Across two studies, performance on simpler versions of planning and working memory tasks reached adult-like performance during adolescence (16–17 years old for planning in Albert and Steinberg (2011) and 13–15 years old for working memory in Luciana, Conklin, Hooper, and Yarger (2005)), but more complex planning and working memory abilities continued to develop into emerging adulthood. Thus, it appears that more basic cognitive control processes, such as inhibitory control, primarily mature through early and into middle adolescence, which is the developmental period of key interest in the current study.

The limited longitudinal data available suggest that performance on the antisaccade task improves from late childhood to young adulthood (Ordaz, Foran, Velanova, & Luna, 2013; Paulsen, Hallquist, Geier, & Luna, 2015). There is also preliminary evidence of curvilinear growth throughout this period, with improvements in error rates (i.e., improvements in inhibition) decelerating with age but continuing through emerging adulthood (Ordaz et al., 2013). However, confidence in these data is limited by high attrition rates (46% attrition across three waves in Ordaz et al., 2013, p. 60% attrition from Wave 1–3 in Paulsen et al., 2015) and the relatively small number of participants in the adolescent years. In one of the few large, longitudinal studies in this area, Bezdjian, Tuvblad, Pan, Adrian, and Baker (2014) demonstrated that omission errors on a Go/No-Go task decrease from late childhood through adolescence, but neither the pattern of change nor the extent of individual differences in change were evaluated.

In contrast to task-based studies, which suggests that improvements in inhibitory control may be curvilinear across adolescence, questionnaire-based measures of impulsivity suggest linear decreases in impulsivity across adolescence (Steinberg et al., 2008) and less impulsivity in a group of emerging adults, relative to middle adolescents (Leshem & Glicksohn, 2007). Longitudinal studies utilizing questionnaire methods also suggest linear decreases in impulsivity across adolescence (Harden & Tucker-Drob, 2011; Lydon-Staley & Geier, 2018), with the caveat that these questionnaires were the summation of two (Lydon-Staley & Geier, 2018) or three (Harden & Tucker-Drob, 2011) available items that did not come from an established scale, leaving open questions about measurement validity.

To summarize, inferences regarding adolescent development of cognitive control systems has primarily relied on cross-sectional data to date. There is a clear need for the longitudinal evaluation of 1) the manner in which inhibitory control develops in adolescence (e.g., linear or curvilinear) and 2) the extent of individual differences in development (Foulkes & Blakemore, 2018; Pfeifer & Allen, 2012). Furthermore, given differences in task versus questionnaire-based measures, incorporating both types of assessment in the same group of adolescents is critical for understanding how measurement selection may impact conclusions regarding developmental change. The current study addresses these important gaps in the literature and takes one step towards placing the adolescent developmental literature on firmer empirical grounds by examining the development of both task-based and questionnaire-based inhibitory control among a large (n = 387; 4% attrition across 3 waves) community sample of adolescents.

1.4. Associations with delinquent behavior

It is well-established that adolescence is a period in which rates of delinquent and antisocial behaviors increase (Moffitt, 1993), and underdeveloped self-regulation is thought to be a central process driving maladaptive outcomes in adolescence. Extant cross-sectional evidence does document the criterion validity of inhibitory control. For example, performance on the Stop Signal Task reliably discriminates between individuals with externalizing disorders and non-clinical populations (Lipszyc & Schachar, 2010) and relates to dimensionally-measured externalizing symptoms (Schoemaker, Mulder, Dekovic, & Matthys, 2013) and substance use (Nigg et al., 2006). Questionnaire indices of effortful control concurrently relate to antisocial behavior (Gardner, Dishion, & Connell, 2008) and substance use (Piehler, Veronneau, & Dishion, 2012), and questionnaires of inhibitory control have shown moderate associations with externalizing behaviors (Muris, Meesters, & Bllijlevens, 2007). There is also some evidence that measures of inhibitory control and related constructs (effortful control, self-regulation, etc.) prospectively predict symptomatology, antisocial behaviors, and substance use in adolescence (e.g., Jurk, Mennigen, Goschke, & Smolka, 2018; Piehler, Véronneau, & Dishion, 2012; Quinn & Fromme, 2010; Rhodes, Colder, Trucco, Speidel, & Hawk, 2013).

However, we are not aware of any study that has examined how both initial levels and *growth* in inhibitory control prospectively predicts delinquent behaviors in adolescence. The importance of evaluating growth is highlighted by evidence that individual differences in growth of effortful control predicts adjustment outcomes across late childhood to early adolescence, above and beyond initial levels of effortful control (King, Lengua, & Monahan, 2013). Furthermore, given that delinquency tends to peak around middle to late adolescence (Moffitt, 1993) and that engaging in externalizing behaviors may reciprocally impact later cognitive control (e.g.,

Table 1
Participant Characteristics.

	Wave 1	Wave 2	Wave 3	Wave 7
Age	12.1 (.59)	13.1 (.59)	14.1 (.61)	18.2 (.49)
Age range	11.0–13.2	12.0–14.4	12.4–16.1	17.0–19.9
Sex (% Female)	55%			
IQ	107.4 (11.2)			
Race/Ethnicity				
% Caucasian	83%			
% African American	9%			
% Hispanic/Latino	2%			
% Asian/Pacific Islander	1%			
% Other/Multi-racial	5%			
Socioeconomic characteristics				
Median family income	70,000			
Range of family income	1500–500,000			
% families receiving public assistance	6%			
EATQ Inhibitory Control				
Mean Rating	3.62 (0.59)	3.68 (0.57)	3.69 (0.57)	
Delinquent Behavior				
T-score	51.3 (3.0)	51.8 (3.6)	52.8 (4.6)	56.3 (7.4)
Mean Items Endorsed	0.12 (0.14)	0.14 (0.16)	0.18 (0.19)	0.27 (0.28)

Note. Unless otherwise stated, values represent the mean (SD). IQ was estimated from the Reynolds Intellectual Screening Test (RIST). EATQ-R = Early Adolescent Temperament Questionnaire – Revised. Delinquent behavior was measured from the rule-breaking behavior subscale of the Youth Self-Report/Adult Self-Report, a child/adult self-report of behavioral and psychological functioning.

Anand, Springer, Copenhaver, & Altice, 2010), it is important to evaluate inhibitory control early in adolescence, *before* most individuals are engaging in delinquent behaviors.

The current study provides a novel examination of the extent to which initial levels (intercept) and growth (slope) in inhibitory control predicts later delinquent behaviors. It was hypothesized that teens with worse inhibitory control in early adolescence would demonstrate greater increases in delinquent behavior from early to middle adolescence and from middle adolescence to emerging adulthood. Faster rates of change in inhibitory control (i.e., steeper growth) were predicted to be associated with less delinquency in both middle adolescence and emerging adulthood.

2. Methods

2.1. Participants

Participants were part of a multi-wave longitudinal study of risk and protective factors for adolescent and young adult substance use (see Colder et al., 2013 for details). The sample was recruited via random digit dialing. Participants were eligible for the study if they were 11–12 years old at recruitment, were free of disabilities that would interfere with their ability to complete the assessments, and had a caregiver willing and able to participate in the study. The response rate was 52%, and the final sample included 387 families (caregiver and adolescent; 88% mothers). The sample was representative of the population from whence it came, with the exception that the current sample had more two-parent households and higher education than is typical for the county (Erie County, NY; see Table 1 for participant characteristics).

2.2. Procedures

This study was approved by the IRB. Parental consent and child assent were obtained at each visit. Both the adolescent and a caregiver attended laboratory visits spaced one year apart for the first three years (Waves 1–3) and another visit four years later (Wave 7). During visits, participants completed a variety of questionnaires assessing temperament, substance use, psychological functioning, family environment, parental behavior, and peer relationships. They also completed several cognitive tasks, including the Stop Signal Task (SST). The version of the SST utilized in this study was only completed at Waves 1–3. Adolescent self-report of delinquent behaviors was collected at Waves 1–3 and Waves 7. Data collection in Waves 4–6 was conducted via an automated phone survey and assessed only substance use variables, which are not the focus of this study. Monetary compensation was provided to both participants and caregivers for Waves 1–3 and Waves 7.

2.3. Measures

2.3.1. Stop Signal Task

The SST measures an individual's speed of inhibition (Logan et al., 1984; Rosch et al., 2016; Verbruggen, Chambers, & Logan, 2013), with factor analytic work suggesting that the SST loads more strongly on a latent inhibition factor than other commonly-used

Table 2
SSRT Descriptive Statistics Across Waves.

	N	α	SSRT	Integration-method RT	Mean Stop Delay	Percent Inhibition
Wave 1	384	.84	176.7 (70.8)	500.0 (95.6)	323.4 (120.5)	48.6 (5.4)
Wave 2	359	.79	143.1 (47.9)	458.6 (90.9)	320.2 (113.1)	49.1 (4.7)
Wave 3	349	.77	133.2 (47.3)	441.5 (87.7)	314.4 (109.0)	48.9 (4.2)

Note. SSRT = Stop Signal Reaction Time; smaller SSRTs represent better inhibitory control.

tasks of inhibitory control (Friedman, Miyake, Robinson, & Hewitt, 2011; Miyake et al., 2000). Task stimuli were 2 × 2 cm white arrows presented on a black background screen. Participants were instructed to press the left and right buttons of a response box whenever the arrow on the screen pointed left or right, respectively (see Rhodes et al., 2013). The task began with a 32-trial "go" practice block to establish the prepotent "go" response. A 32-trial "stop" practice block followed; teens were instructed to inhibit responding when the arrow was followed by the stop signal, a 1000-Hz tone presented on 25% of trials. The delay between the stimulus presentation and stop signal (i.e., stop signal delay or SSD) began at 350 ms and adjusted dynamically in 50 ms increments to result in approximately 50% inhibition.

After practice blocks, participants completed six test blocks of 64 trials each (384 trials total), with a brief break between blocks three and four. Blocks four to six involved feedback in the form of stars and points for correct responding. Test trials included a 500 ms fixation period, 1000 ms stimulus presentation, 1000 ms response period, 1000 ms feedback period, and 500 ms ITI. The feedback screen during the no-reward block contained an uninformative stimulus (a square), and feedback during the reward block included stars of varying shapes and colors that corresponded to trial type (go vs. stop) and speed of response. There was no evidence that reward affected performance, so blocks were averaged across reward condition (at each wave, SSRTs between reward and no-reward blocks were similar, *ts* = 1.2, 1.0, 1.4, *ps* = .24, .32, .14, *ds* = 0.06, .05, .08 for Waves 1–3, respectively).

Stop Signal Reaction Time (SSRT) estimates the speed of inhibition and is the primary outcome variable from the SST (SSRT = integration RT – mean stop signal delay). It was computed using the integration method (Verbruggen et al., 2013), which accounts for differences in inhibition rates and is robust to slowing and variability in responding during the task. Blocks of trials with negative SSRTs and with inhibition rates lower than 20% or greater than 80% were excluded, as in prior work (Congdon et al., 2012; Nigg, 1999). These criteria resulted in the exclusion of 0.8%, 3.8%, and 5.6% of blocks in Waves 1–3, respectively. Acceptable reliability was demonstrated at all waves (see Table 2).

2.3.2. Early Adolescent Temperament Questionnaire – revised

The Inhibitory Control subscale of the parent-reported Early Adolescent Temperament Questionnaire-Revised (EATQ-R; Ellis & Rothbart, 2001) was used as the questionnaire indicator of inhibitory control. Parents rated their children on a 1 to 5 Likert scale on a series of five items assessing their child's ability to plan and inhibit inappropriate responses (e.g., "is able to stop him/herself from laughing at inappropriate times"), with higher scores reflecting greater control. Internal consistency reliability was poor in the current sample (α′s = .51, .58, and .60 across Waves 1–3), which is consistent with estimates from other studies (e.g., Muris, Meesters, & Blijlevens, 2007). Despite the low internal consistency reliability, scores demonstrated consistency across Waves (ICC = 0.66), and there is evidence that the inhibitory control subscale relates to measures of self-regulation and behavioral outcomes in a theoretically-consistent manner (Muris et al., 2007).

2.3.3. Achenbach System of Empirically-Based Assessment

Delinquent behavior was measured with the rule-breaking subscale from the Achenbach System of Empirically-Based Assessment (ASEBA; Achenbach, 2009). ASEBA measures include items to which the target responds on a Likert scale (0 = Not True, 1 = Somewhat or Sometimes True, 2 = Very True or Often True) to indicate how well each statement describes themselves. The Youth Self-Report (YSR) provided an index of the participant's behavior in early (Wave 1) and middle adolescence (Wave 3). The Adult Self-Report (ASR) is a developmentally-appropriate extension of the YSR that was utilized in emerging adulthood (Wave 7). The 15-item rule-breaking subscale items assess a range of delinquent/externalizing behaviors and risk factors, including substance use (e.g., "Drinks alcohol without parents' approval), affiliation with deviant peers (e.g., "Hangs around with other who get in trouble), lying/stealing, breaking rules, and stealing outside the home. Because T-scores are not appropriate for assessing developmental changes, the mean endorsement of items was computed at each wave. Internal consistency was adequate at all waves (α′s = 0.68, .77, and .84 for Waves 1, 3, and 7, respectively).

2.3.4. Covariates

Covariates were collected at the Wave 1 assessment. Intellectual functioning was estimated with the Reynolds Intellectual Screening Test (RIST; Reynolds & Kamphaus, 2003). Previous psychometric evaluations have demonstrated excellent internal consistency reliability (> .90), and moderate-to-strong correlations with other measures of IQ and with measures of achievement (Nelson & Canivez, 2012; Reynolds & Kamphaus, 2003). Parents reported their children's sex and self-reported their family's income on a demographic form.

2.4. Data analytic plan

Growth in inhibitory control was analyzed with latent growth curve models with individual varying times of observation. Due to the generally low correlation between task and questionnaire measures (*r*s between SSRT and EATQ-R scores ranged from .16 to .18 in the current sample; see also Duckworth & Kern, 2011), the SST and EATQ-R were examined in separate models. Due to skewness in the distributions of SSRT and delinquency, maximum likelihood robust (MLR) estimation was used. Change in inhibitory control over time was modeled on continuous age, rather than assessment wave. The intercept was centered at age 11. The baseline model was an intercept-only model. Nested log-likelihood difference tests were used to determine whether adding a linear slope improved model fit. Finally, we evaluated whether the addition of a fixed quadratic trend improved model fit. Given the novelty of longitudinal inhibitory control data in adolescence, in exploratory analyses we evaluated whether child IQ, child sex, or parental income predicted the intercept and slope.

To examine whether individual differences in the intercept or slope of inhibitory control predicted changes in delinquent behaviors, Wave 3 rule-breaking scores were first regressed on the intercept and slope, controlling for Wave 1 scores (see Colder et al., 2013). We then evaluated whether the intercept or slope of inhibitory control was associated with increases in delinquent behaviors from middle adolescence to emerging adulthood. Wave 7 (*M* age = 18.2) rule-breaking scores were regressed on the intercept and slope, controlling for Wave 3 scores. All models included child IQ and sex as covariates. Note that standardized parameter estimates are not available when individual varying times of observation are used, so unstandardized estimates are presented.

3. Results

The retention rate from Wave 1 to Wave 3 was 96%, and retention at Wave 7 was 91%. Families who completed all waves of data collection did not differ from those who dropped out ($n = 33$) on demographic characteristics, Wave 1 rule-breaking behavior, Wave 1 SSRT, or Wave 1 Inhibitory Control scores, all Fs < 1.5, all ps $> .25$.

3.1. Growth of inhibitory control

For task-based inhibitory control, nested model tests revealed that adding a linear slope improved model fit, $\Delta\chi^2$ (3) = 46.2, $p < .001$. Including a fixed quadratic trend also improved model fit, $\Delta\chi^2$ (1) = 28.1, $p < .001$. Significant variance was observed in the intercept ($\sigma^2 = 3841$, $p < .001$) and slope ($\sigma^2 = 236$, $p = .023$), indicating there were significant individual differences in initial levels of inhibitory control and in the rate of change over time. The intercept and linear slope were significantly related (covariance = −768.1, $p = .002$), such that worse inhibitory control at age 11 (higher SSRTs) was associated with a steeper rate of improvement in inhibitory control across time. In this final model with a random intercept, random linear slope, and fixed quadratic slope, the average SSRT at age 11 was 206 ms and showed both a linear, $b = -39$ ms, $p < .001$, and quadratic decline across age, $b = 5$ ms, $p < .001$ (see Fig. 1a). Child IQ, sex, and parental income did not predict initial levels (intercept) or growth (linear slope) of task-based inhibitory control, all ps $> .24$.

For parent-reported inhibitory control, including a linear slope did not improve model fit, $\Delta\chi^2$ (3) = 4.9, $p > .10$, and the slope was non-significant, $b = 0.02$, $p = .22$, suggesting no detectable changes in parent-reported inhibitory control over time (see Fig. 1b). Significant variance in the intercept was observed ($\sigma^2 = 0.22$, $p < .001$), and the average score at age 11 was 3.66 (possible range = 1–5). Girls ($b = 0.14$, $p = .005$), teens with higher IQs ($b = 0.007$, $p = .004$), and those with higher parental income ($b = 0.02$, $p = .001$), had higher parent-reported inhibitory control at age 11.

3.2. Associations with delinquent behavior

Contrary to predictions, neither the intercept ($b = 0.0001$, $SE = 0.0001$, $p = .48$) nor slope ($b = 0.0001$, $SE = 0.003$, $p = .99$) of task-based inhibitory control predicted delinquent behaviors in middle adolescence. However, worse inhibitory control in early adolescence (i.e., higher SSRTs at age 11, the intercept) predicted increases in delinquency from middle adolescence to emerging adulthood ($b = 0.001$, $SE = 0.001$, $p = .05$). Individual differences in the rate of change (slope) in inhibition across early to middle adolescence was unrelated to delinquent behavior in emerging adulthood ($b = 0.006$, $SE = 0.05$, $p = .90$).

Because there was no evidence of growth in parent-reported inhibitory control, only the intercept was used in prediction models. For parent-reported inhibitory control, lower scores in early adolescence (i.e., the intercept) were predictive of greater increases in delinquent behaviors from early to middle adolescence ($b = -0.15$, $SE = 0.002$, $p < .001$). Similarly, lower inhibitory control ratings in early adolescence were associated with steeper increases in delinquent behavior from middle adolescence to emerging adulthood, ($b = -0.16$, $SE = 0.007$, $p < .001$).

4. Discussion

Learning to regulate behavior in pursuit of longer-term goals is a critical developmental task of adolescence. Inhibitory control is a key component of self-regulation; successful inhibition involves preventing oneself from engaging in a dominant, prepotent behavior, or stopping a behavior that has already been initiated. Although inhibitory control is central to current theoretical models of adolescent brain development that suggest gradual improvement in inhibitory control during adolescence (Casey et al., 2008; Steinberg, 2008), longitudinal studies are sparse and have not focused on growth within the adolescent period, precluding strong tests of developmental changes occurring within the adolescent years. The current study provided a longitudinal evaluation of the normative

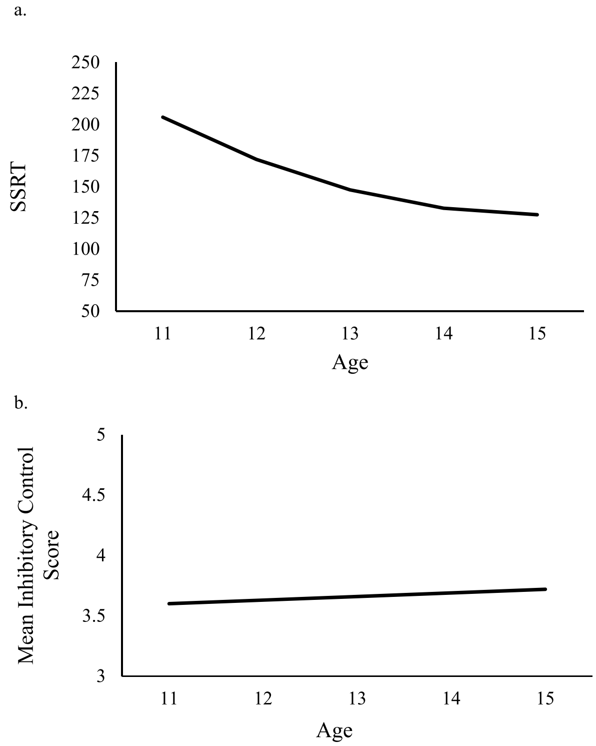

Fig. 1. Model-Derived Growth Patterns.
Note. Growth curves represent a) stop signal reaction time (SSRT) and b) parent-reported inhibitory control on the EATQ-R. Decreases in SSRT represent improved inhibitory control, and higher scores on the EATQ-R reflect better inhibition. Note that that full range of the EATQ-R is 1–5.

development of inhibitory control from early to middle adolescence utilizing both task and questionnaire measures.

4.1. Development of inhibitory control in adolescence

Across three annual assessments with a community sample that spanned 11–15 years old, task-based inhibitory control (Stop Signal Task) demonstrated strong linear growth that slowed around middle adolescence (see Fig. 1a). The slowing of growth in middle adolescence could suggest that maturation of inhibitory control occurs earlier than young adulthood, or at least slows its rate of maturation, relative to other higher-order functions. Although there is evidence that the complex cognitive control system develops into young adulthood (Friedman et al., 2016; Shaw et al., 2008), inhibitory control is a lower-level facet of cognitive control. Lower-level processes develop sooner than the higher-order processes, so it is possible that inhibition reaches maturity before other aspects of cognitive control (see Nigg, 2017). Indeed, a cross-sectional study of age-related changes in SST performance showed that performance peaked in the adolescent group (13–17 years old), rather than the young adult group (Williams et al., 1999). This hypothesis is also consistent with previous cross-sectional work showing that the age at which adolescents reach adult-like performance depends on the difficulty of the task (Luciana et al., 2005). For example, Albert and Steinberg demonstrated that teens in the 16-17-year-old age group performed just as well as adults on easy problems, but age-related improvements were observed on the most challenging problems until the 22-25-year-old age range (Albert & Steinberg, 2011). Taken together, the evidence strongly suggests that the difficulty level of a study's tasks needs to be appropriately matched to the age range of study participants, as well as the research question of interest (i.e., using simpler cognitive control tasks such as a Go/No-Go or tasks of working memory that place relatively little demands on the central executive may be inappropriate to evaluate developmental changes from early adolescence through adulthood).

In contrast to task-based results, parent-reported inhibitory control (Early Adolescent Temperament Questionnaire-Revised) did not demonstrate growth over time. This pattern is consistent with findings from other studies using similar measures. For example, Steinberg et al. (2008) utilized cross-sectional data to evaluate age-related changes in impulsivity and found that the mean of self-reported impulsivity on the Barratt Impulsivity Scale (Patton, Stanford, & Barratt, 1995) in the 10–11 age group was 13.31 and dropped to 13.21 in the 14–15 age group, corresponding to a very small effect size ($d = 0.04$). Generally, studies using task-based assessments are also more likely to document non-linear changes than studies using questionnaire-based assessments (e.g., Albert & Steinberg, 2011; Steinberg et al., 2008). These cross-method differences cannot solely be attributed to study differences because the current results also differed across methods, despite the data being collected in the same individuals. Rather, it highlights that the selection of a measurement instrument can significantly impact the conclusions drawn regarding developmental changes, and researchers should carefully consider whether task- or questionnaire-based tools are most appropriate for a given research question (see

Measurement Considerations below).

4.2. Associations with delinquent behavior

There is significant evidence that inhibitory control and other self-regulatory processes are associated with important psychosocial outcomes in childhood (Friedman et al., 2011; Lengua, 2003). However, empirical evidence linking inhibitory control to adjustment during the teenage years is lacking (see Bjork, Lynne-Landsman, Sirocco, & Boyce, 2012; Johnson, Blum, & Giedd, 2009). Existing work has largely involved concurrent, cross-sectional relations (e.g., Nigg et al., 2006) or prospective associations across two time points (Quinn & Fromme, 2010; Rhodes et al., 2013). To our knowledge, no previous study has longitudinally examined how individual differences in the rate of growth of inhibition contributes to risk of maladaptive outcomes in adolescence.

Across both task- and questionnaire-based assessments of inhibitory control, teens with worse inhibition in early adolescence (i.e., intercept) demonstrated greater increases in delinquency from middle adolescence (ages 13–15) to emerging adulthood (ages 17–19). Worse parent-reported inhibition also predicted greater increases in delinquency from early to middle adolescence, but task-based inhibitory control was unrelated to middle-adolescent delinquency. Task-based inhibitory control's relation to later-adolescent, but not middle-adolescent, delinquency is somewhat surprising because of the timing of assessments of the predictor and outcomes. At the same time, teens are monitored more closely by parents in early and middle adolescence (Keijsers & Poulin, 2013; Laird, Pettit, Bates, & Dodge, 2003), so parents may act as an external regulator during this time. As teens gain more autonomy, learn to drive, leave home, etc., they become more reliant on their own self-regulatory abilities; thus, the “true” magnitude of the association between a trait-like variable and behavioral outcomes may be strongest when other external influences (e.g., parental supervision) are attenuated (Allen & Miga, 2010).

Contrary to hypotheses, individual differences in the rate of growth in task-based inhibitory control did not predict later delinquent behavior at any time point, which is inconsistent with some previous work using measures of effortful control or executive function in younger children (Hughes & Ensor, 2011; King et al., 2013). Several caveats should be noted regarding the finding that the intercept but not slope predicted risk in emerging adulthood. First, there was more variance (i.e., individual differences) in the intercept than the slope. This is common in growth models (Bollen & Curran, 2005), and a variable's variance impacts its ability to correlate with other variables (Furr & Bacharach, 2014). Second, growth is constrained by one's starting point, as is evident by the strong covariance between the intercept and slope. Teens who had strong inhibition at age 11 generally had less steep slopes. This could be related to maturation, as less growth was required for those teens' inhibitory control to reach adult levels, but it could also be a methodological issue of ceiling/floors effects. Though we utilized an inhibitory control task that appears to best capture the process of interest (Friedman et al., 2011), the reliance on RTs may constrain the degree of improvement possible over time. Future research using various methods will be important for evaluating whether individual differences in growth are, in fact, unrelated to later delinquency, or whether certain measures are better suited for capturing the association between growth and adjustment. Future work could also select at-risk youth with low initial levels of inhibitory control, which would mitigate concerns about ceiling/floor effects.

4.3. Measurement considerations

Although both task and parent-reported inhibitory control assessments predicted increases in delinquency from middle adolescence to emerging adulthood, results notably diverged in terms of growth over time. These differences across measurements are not surprising, given that tasks and questionnaires intended to measure the same construct are often weakly correlated (Duckworth & Kern, 2011). This may be largely driven by the properties of each assessment tool, and these measurement differences likely make task and questionnaire-based assessments useful for different research questions.

Questionnaire-based assessments tend to be highly stable over time, in part because of the time frame of assessment. The EATQ-R asks parents to rate their child's behavior *over the past year*. Parents are therefore aggregating hundreds of data points into their responses to report on how their child generally behaves. These measurement characteristics result in high stability over time, in part because parents may not be sensitive to small changes in their child's behavior and may not update their impressions of their child accordingly (Tobler & Komro, 2010). This possibility is particularly relevant as children move throughout adolescence and parents spend less time with them.

In contrast, laboratory tasks capture an individual's performance at a single point in time and represents not only an individual's level of inhibitory control, but also state factors influencing performance on the day of assessment (e.g., how much they slept the night before the assessment, their mood, caffeine consumption, etc.). Additionally, the Stop Signal Task used in the current study is a reaction-time-based measurement, and the range of potential scores is much larger than the range of scores on the EATQ-R. The greater range makes the task measure more sensitive for detecting change and individual differences in change, which we observed in the present study.

Given the differences in score variability and stability, questionnaire-based assessments may be most useful when the goal is to capture stable between-person individual differences. Task-based assessments may be preferable when examining within-person changes due to acute manipulations (e.g., reinforcement/punishment, presence of peers, etc.) or developmental changes over time (Hedge, Powell, & Sumner, 2018). These measurement considerations have important implications for the neuroimaging initiatives that are currently underway because task-based fMRI performance is subject to similar state influences/reliability concerns as the Stop Signal Task.

4.4. Limitations and future directions

The present study has a number of notable strengths, including the community sample, high retention rate, and use of both task and questionnaire assessments of inhibitory control. Yet, due to funding constraints, we were unable to extend the evaluation of inhibitory control into the late adolescent and emerging adult years. We were also limited in having a single task and questionnaire, whereas it would be ideal to have multiple indicators of the construct for each method, especially because the internal consistency reliability of parent-reported inhibitory control was poor. The current reliability estimates of the Inhibitory Control subscale of the EATQ-R are not unique to our sample (Muris et al., 2007); future work may need to develop measures that can reliably assess the more basic inhibitory processes that serve as the building blocks for complex self-regulatory processes. At the same time, the measure demonstrated strong correlations across time and related to theoretically-meaningful variables, showing evidence of test-retest reliability and criterion validity, respectively.

Most research to date on inhibition in adolescence uses dimensionally-measured scores to predict some adverse outcome, which was the approach taken in the current study. This is an important starting place for establishing the construct validity of inhibitory control in adolescence, but in order to maximize clinical utility, the field will eventually have to move beyond the notion that individual differences in inhibition relate to individual differences in some outcome to identify levels of inhibition that confer risk of clinically-significant outcomes. To that end, though our recruitment strategy is ideal for the present goal of evaluating normative changes in inhibitory control, it was not particularly well-suited to identify high-risk adolescents, and results of the current study may not generalize to these at-risk groups.

Finally, we focused exclusively on inhibitory control in the current study because detailed investigations of how inhibition develops within adolescence are lacking. However, top-down cognitive control processes are modulated by motivational factors (Casey, 2015), including approach vs. avoidance motivation (Crone, van Duijvenvoorde, & Peper, 2016; Nigg et al., 2006; Rhodes et al., 2013) and social context (Crone & Dahl, 2012). Moving forward, it will be necessary to examine how inhibitory control interacts with person-level factors (e.g., reward sensitivity, avoidance motivation; Rhodes et al., 2013) and environmental factors (e.g., inclusion in a deviant peer group, level of parental monitoring; Crone & Dahl, 2012) to confer or mitigate risk of maladaptive outcomes in adolescence.

5. Conclusion

In a longitudinal study evaluating the development of inhibitory control in a large community sample of adolescents, we found that inhibition improves from early to middle adolescence, with some evidence that growth may slow in the middle adolescent period. We further provided evidence that early-adolescent inhibitory control is associated with increases in delinquent behavior in emerging adulthood. If replicated, results indicate that the degree to which inhibitory control confers risk for late-adolescent delinquency may be captured in early adolescence, consistent with neurodevelopmental accounts of delinquency risk and of central importance to prevention science. This developmental description informs – and constrains – theory and provides a novel examination of inhibitory control during the first half of the critical adolescent period. It highlights the need for research that documents the full developmental course of inhibitory control throughout adolescence and the need for careful consideration of assessment tools depending on a study's goal. These advances are critical next steps in moving towards understanding the role of inhibition in predicting, and perhaps eventually preventing or mitigating, maladaptive adolescent outcomes.

Declarations of interest

None.

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