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Apples to apples? Neural correlates of emotion regulation differences between high- and low-risk adolescents

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Abstract

Adolescence has been noted as a period of increased risk taking. The literature on normative neurodevelopment implicates aberrant activation of affective and regulatory regions as key to inhibitory failures. However, many of these studies have not included adolescents engaging in high rates of risky behavior, making generalizations to the most at-risk populations potentially problematic. We conducted a comparative study of nondelinquent community ($n = 24$, mean age = 15.8 years, 12 female) and delinquent adolescents ($n = 24$, mean age = 16.2 years, 12 female) who completed a cognitive control task during functional magnetic resonance imaging, where behavioral inhibition was assessed in the presence of appetitive and aversive socioaffective cues. Community adolescents showed poorer behavioral regulation to appetitive relative to aversive cues, whereas the delinquent sample showed the opposite pattern. Recruitment of the inferior frontal gyrus, medial prefrontal cortex, and temporo-parietal junction differentiated community and high-risk adolescents, as delinquent adolescents showed significantly greater recruitment when inhibiting their responses in the presence of aversive cues, while the community sample showed greater recruitment when inhibiting their responses in the presence of appetitive cues. Accounting for behavioral history may be key in understanding when adolescents will have regulatory difficulties, highlighting a need for comparative research into normative and nonnormative risk-taking trajectories.

Key words: adolescent delinquency; emotion regulation; fMRI; neurodevelopment; social processing

Introduction

Adolescence is often described as a paradoxical time, where relative improvements in certain domains (e.g. abstract reasoning) are often coupled with suboptimal decision making in other domains (e.g. health risk behaviors; Brener *et al.*, 2013). Much of this paradox has been attributed to the outsized role that affective processing plays in adolescents' lives (Somerville, Hare & Casey, 2011). Specifically, adolescents' ability to regulate their

behavior is particularly affected by socioaffective cues (Chein *et al.*, 2011; Casey, 2015), which may explain the onset of negative outcomes like psychopathology (Kranzler *et al.*, 2016) and increased risk taking (Casey *et al.*, 2008; Guyer *et al.*, 2011; Nelson *et al.*, 2005; Pfeifer *et al.*, 2011; Perino *et al.*, 2016; Somerville *et al.*, 2011), and rises in delinquency (Moffitt & Caspi, 2001). Developmental neuroscience research has speculated that suboptimal behaviors like delinquency may be driven, in part, by neural changes that make adolescents more susceptible to disinhibited

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responses. While such work has aided in theorizing how neuroscience can inform the treatment of adolescents engaging in high rates of disruptive behaviors (Cohen & Casey, 2014; Casey et al., 2017), it is unclear if these normative increases in risk taking are explanatory for the youth actively engaging in high-risk behaviors.

Neuroscientific inquiries have found socioaffective stimuli—both negatively and positively valenced—to impact regulation in adolescents, although the specific effect has not been consistent. A number of studies have found that aversive stimuli—such as fearful faces (Grose-Fifer, et al., 2014; Monk et al., 2003), negative affective images (Cohen-Gilbert & Thomas, 2013), and threat cues (Dreyfuss et al., 2014)—are particularly deleterious to regulatory capacities, whereas others have found that compromised regulation may be more specific to appetitive stimuli—such as happy faces (Somerville et al., 2011), positive affective images (Perino et al., 2016), and the presence of peers (Chein et al., 2011). The nature of this discrepancy is of great importance, as it suggests adolescent dysregulation in response to socioaffective stimuli is complex and likely driven by more than merely the type of stimuli observed.

Such divergent findings may be reflective of differences in the participants' lived experiences. For example, increased focus on appetitive socioaffective cues may theoretically help adolescents identify and act on opportunities to increase their status within their respective social hierarchies (Nelson, Jarcho, & Guyer, 2016). Not all social groups are alike, and for some adolescents, dysregulation in aversive or threatening situations may place them at an increased risk of negative consequences. Furthermore, research has shown that environmental inputs often change behavior (Bronfenbrenner, 1979), with a particular focus on the impact of unstable environments and their role in behavioral reactivity (Ellis et al., 2012). What is valuable within a given environment will vary, and the socioaffective cues relevant to those consistently engaging in delinquency may fundamentally differ from their nondelinquent community counterparts. Perhaps those engaging in delinquency demonstrate behavioral and neural adaptations necessary for surviving and rising in disruptive environments (Ellis et al., 2012). Alternatively, past delinquent behavior may alter processing that impacts future decision making in ways not applicable to normative samples (Agnew, 1992). To better understand how affective processing difficulties may lead some adolescents astray, more inquiries need to focus on how, when, and for whom affective stimuli are problematic, as increased generalizability to diverse samples may highlight developmental issues currently overlooked (Telzer, 2018).

The interplay between subcortical affective circuitry and regulatory cortical regions has been highlighted in accounts of adolescent disinhibition. Volumetric and functional changes in social cognition regions [e.g. the fusiform face area, superior temporal sulcus, and temporoparietal junction (TPJ)]; Blakemore & Mills, 2014) and increases in neural activation of affective circuitry (e.g. amygdala (Guyer et al., 2008), ventral striatum (Galvan, 2010)), coupled with aberrant activity in regulatory regions [e.g. inferior frontal gyrus (IFG), medial prefrontal cortex (mPFC); Crone & Dahl, 2012], are reported in functional magnetic resonance imaging (fMRI) research with adolescent samples. These neural changes are proposed to reorient cognitive resources toward salient socioaffective cues and away from regulatory processing (Nelson et al., 2005; Somerville et al., 2011; Nelson et al., 2016; Perino et al., 2016). The amygdala and ventral striatum show greater responsivity to appetitive socioaffective cues in adolescence, which may override inhibition (Somerville

et al., 2011; Perino et al., 2016). The recruitment of prefrontal regions implicated in executive functioning [such as the IFG (Aron, Robbins & Poldrack., 2014) and the mPFC (Dreyfuss et al., 2014)] is necessary to successfully inhibit and override the attentional resources engaged in the presence of salient affective cues (Theeuwes, 2010). Given the role these regulatory regions have shown in successful inhibition in the presence of salient stimuli (Serences et al., 2005; Sharp et al., 2010; Swann et al., 2012; Aron et al., 2014), they likely play a key role in adolescents' ability to successfully focus on the task at hand and away from distracting salient information (Fukada & Vogel, 2009; McCormick & Telzer, 2017; McCormick et al., 2016).

In the current study, a low-risk community and high-risk delinquent sample of adolescents completed a modified go/no-go task (Cohen-Gilbert & Thomas, 2013) during which participants were instructed to inhibit a prepotent behavioral response while distracted by socioaffective cues, which were either appetitive or aversive social stimuli. We assessed how the presence of these cues differentially impacted inhibitory and neural responses. By comparatively assessing the influence of socioaffective cues on both delinquent and community adolescents, we aimed to extend normative neurodevelopmental work into a high-risk population. There is a need to test whether regulatory problems observed in delinquent adolescents are different from their community peers in terms of the magnitude (i.e. same patterns of behavior and brain across appetitive and aversive contexts, but higher overall deficits in the delinquent sample) or context (i.e. different patterns of behavior and brain across appetitive and aversive contexts) in order to correctly conceptualize disinhibition leading to psychosocial dysfunction.

On the one hand, current theory suggests social reorientation may impact all adolescents along a continuum (Nelson et al., 2016), such that the patterns of behavioral and neural processes are pointed in the same direction, in which case delinquent adolescents may represent more extreme examples of disinhibition relative to their nondelinquent community counterparts (Young et al., 2009). However, we argue that, rather than showing overall greater difficulty to the same cues, delinquent adolescents' disinhibition may differ based on the socioaffective context they are experiencing. Adolescents with behavioral issues may have adapted to their environment in such a fashion that social reorientation directs attention to cues of threat or those that evoke aversive affective states. Thus, adolescents engaging in disruptive behaviors may find aversive cues more salient, as this may signify oncoming danger, whereas appetitive cues may be more salient for nondelinquent samples, as processing these cues may provide adolescents opportunities to rise in their social hierarchy. In other words, the process of a social reorientation may be universal, in that attentional resources at this developmental stage are disproportionately directed toward socioaffective cues in the environment (Nelson et al., 2016), but the cues that are salient may differ based on life experience and behavioral profile. Clarifying the nature of inhibitory responses to socioaffective cues in adolescence may provide valuable insight into explaining what differentiates those undergoing normative development from those actively engaged in high-risk behaviors.

In the current study, we hypothesized that socioaffective cues would lead to greater recruitment of attentional resources (Theeuwes, 2010) and greater disruption in task performance in an implicit emotion regulation task. We predicted that the emotion regulation difficulties observed in the task would depend on the behavioral profiles (low-risk community, high-risk delinquent) of the adolescents. Specifically, community youth will show greater disruption to appetitive cues (Perino et al., 2016),

Table 1. Demographic information for community and delinquent adolescents

	Community sample (n = 24)	Delinquent sample (n = 24)
Age, mean (SD), range	15.8 (.36), 15.5–16.5	16.2 (1.2), 13.1–17.8
No. female	12	12
No. white	17	12
No. black	3	12
No. other ethnicity	4	0

Table 2. Disciplinary history of delinquent sample

	No. of times disciplinary act occurred							
	1	2	3	4	5	6	7	8+
Suspensions	8.3%	16.7%	25%	0%	4.2%	0%	0%	41.7%
Expulsions	41.7%	12.5%	4.2%	0%	0%	0%	0%	0%
Arrests	25%	8.3%	0%	4.2%	4.2%	0%	8.3%	0%

while high-risk youth will show greater disruption to aversive cues (Casey et al., 2017).

Methods

Participants

A total of 51 adolescents were recruited, with a total of 48 adolescents included in the final sample after removing participants unsuitable for analyses [one participant was removed due to an inability to adequately complete the scanning protocol (as determined by poor task comprehension during training and excessive movement throughout the scanning protocol), and two others chose to not complete the scanning session]. The community and delinquent sample each included 24 participants (see Table 1 for demographic breakdown of both samples). Given that disciplinary contacts with school (e.g. suspensions and expulsions) and legal institutions (e.g. arrests) in adolescence have been linked with continued criminal behavior (Wald & Losen, 2003; Weiner, 2003; Rocque & Paternoster, 2011), we recruited participants engaging in antisocial behaviors that resulted in institutional involvement (e.g. property theft, fighting, drug use and/or sale, weapon use, etc. leading to disciplinary actions). We recruited the delinquent sample from (i) an alternative school for students who have been expelled or suspended (ii), the local juvenile detention center, and (iii) the local parole and probation office. To provide greater clarity regarding the scope of delinquency and institutional discipline, the numbers of suspensions, expulsions, and arrests were collected in the delinquent sample (Table 2). Participants in the community sample were recruited from traditional schools in the same geographic area. Participants were compensated US \$50. Informed consent and assent were obtained for participants in accordance with the university's institutional review board.

Experimental paradigm: Go/No-Go and social Go/No-Go task

While completing an fMRI scan, participants completed both a control go/no-go, which was used solely to establish baseline cognitive performance in the absence of socioaffective cues, and a social go/no-go task (Perino et al., 2016) adapted from prior research (Cohen-Gilbert & Thomas, 2013), which was used to assess emotion regulation in the context of socioaffective

cues. The control go/no-go task consisted of four blocks, each containing 25 trials. The control task was completed prior to the social go/no-go, which included four aversive and four appetitive blocks, which were presented in a randomized order. Participants were presented with blocks of socially appetitive or aversive scenes for 300 ms, after which a letter was superimposed on the image for 500 ms. During this 500 ms window, participants were instructed to respond as quickly as possible by pushing a button for every letter shown ('go') except the letter 'X' ('no-go'). The control go/no-go task was identical in design structure, but did not include superimposed images (rather, a white square was presented on a black screen for 300 ms, after which a black letter was superimposed on the white background for 500 ms). In both task variants, 28% of the trials were no-go trials, which created a prepotent response to press, requiring inhibition on no-go trials. A jittered Intertrial interval (ITI) was presented between trials, averaging 1200 ms. In total, the social go/no-go consisted of 100 trials per condition across eight randomized blocks. Socially appetitive blocks included scenes of people celebrating, cooperating, and being affiliative, while socially aversive blocks included scenes of people excluding one another, bullying peers, and showing negative affect (see Perino et al., 2016 for selection and reliability of the stimuli). The task was programmed and presented using E-Prime 2.0 (2012).

To assess for behavioral performance, we chose to use d' as our behavioral measure of emotion regulation (Cohen et al., 2016). d' is an index originating from signal detection theory in which the normalized rate of correct discrimination of a signal ('hits') is compared to the normalized rate of false attributions of signal due to noise ('false alarms') (Green & Swets, 1966; Stanislaw & Todorov, 1999). Given that socioaffective stimuli may alter a number of psychological processes, d' is an ideal metric given its incorporation of multiple signal (correct hits and correct inhibition) and noise (incorrect misses and false alarms) components. In this experiment, a 'hit' was defined as making a button press when appropriately required to (i.e. on go trials), and a false alarm was defined as making a button press when inappropriate to do so (i.e. on no-go trials). d' was calculated for each participant by subtracting their normalized (Z) score of false alarm rates from their normalized (Z) score of hit rates; thus, d' for each condition equaled $Z_{\text{Hit}} - Z_{\text{False Alarm}}$ (Macmillan & Creelman, 1991). d' was calculated separately for socially appetitive and socially aversive blocks as well as the baseline control task. Calculating d' within condition provided an index of how

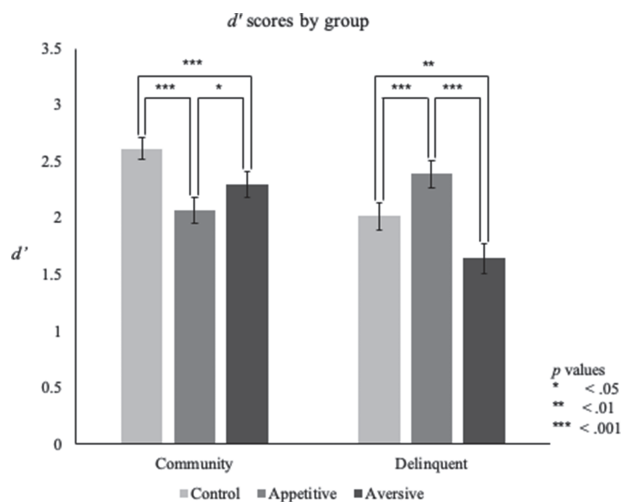


Fig. 1. Within-group comparisons of d' as a function of task condition

well participants performed with and without affective stimuli, where greater d' values indicate better performance on the task (i.e. more effective inhibition coupled with less disinhibition). Utilizing a control go/no-go is optimal for establishing baseline rates of inhibitory control. Given that emotional stimuli are more engaging than the control condition, and our stated focus on how adolescent decision making is specifically affected in social contexts (Nelson et al., 2016), we examined how socioaffective cues (appetitive versus aversive) may have distinct effects on emotion regulation on the social go/no-go.

fMRI data acquisition

Imaging data were collected with a 3 T Siemens TRI MRI scanner. T2*-weighted, matched-bandwidth, high-resolution anatomical scan [repetition time (TR)=4 s; echo time (TE)=64 ms; field of view (FOV)=230; matrix=192x192; slice thickness=3 mm; 38 slices], and T1* magnetization-prepared rapid-acquisition gradient echo (MPRAGE; TR=1.9 s; TE=2.3 ms; FOV=230; matrix=256 x 256; sagittal plane; slice thickness=1 mm; 192 slices) scans were acquired as structural images. Each condition of the experimental paradigm comprised 120 T2-weighted echoplanar images (EPI; slice thickness=3 mm, 38 slices; TR=2 s; matrix=92x92; FOV=230 mm; voxel size of 3x3x3 mm). An oblique axial orientation was used to maximize coverage area and reduce signal dropout for the T2 images.

fMRI data preprocessing and analysis

Data preprocessing and analysis were conducted using Statistical Parametric Mapping (SPM8; Wellcome Trust Centre for Neuroimaging, University College, London, UK). Functional images were spatially realigned in order to correct for movement (no participant exceeded 3 mm of maximum image to image motion in any direction for more than 5% of their echoplanar images). The images were coregistered to each participant's high-resolution MPRAGE and segmented into cerebrospinal fluid, gray matter, and white matter. A normalization transformation matrix was applied to the functional and T2 structural images, thereby converting each participant's data into the standard

stereotactic space specified by the Montreal Neurological Institute. Normalized functional data were smoothed using an 8-mm Gaussian kernel (full width at half maximum). A restricted maximum likelihood algorithm, with an autoregressive model order of 1, was used to address serial autocorrelations, and a high-pass filter with a 128-s cutoff was applied to remove low-frequency noise.

Data were analyzed using the general linear model (GLM) in the SPM software. At the individual level, a fixed-effects analysis was modeled with a block design, in which all individual trials were modeled within each block (800-ms duration) for each condition (socially appetitive, socially aversive), so that null events (i.e. jittered ITIs) served as the implicit baseline. To model inhibitory processing, a parametric modulator (PM) was included for each trial in participants' first level model for the conditions of interest (appetitive or aversive socioaffective cues) to represent behavioral accuracy. We represented successful completion of an individual trial, such that 1 = correct response (correct hit or 'go' and correct inhibition or 'no-go') and 0 = incorrect response (incorrect hit or 'false alarm' and not responding on go trials 'miss'). The PM isolates neural responses linked to behavioral performance on the task (i.e. successful inhibition relative to failed inhibition), allowing us to identify regions specifically recruited for successful relative to unsuccessful behavioral performance. Significant voxels represent brain regions that show parametrically greater activation to correct versus incorrect trials based on the given condition of interest (socially appetitive or socially aversive).

Parameter estimates from the GLM were used to create linear contrasts for comparisons of interest (socially appetitive > socially aversive) at the group level. Random-effects, whole-brain analyses were conducted in order to examine group differences between delinquent and community adolescents. To correct for multiple comparisons at the group level, we conducted a Monte Carlo simulation using the AFNI software package's 3dClustSim command for the group-level brain mask (Ward, 2000) and corrected for intrinsic smoothing, which was estimated using the 3dFWHMx command and acf. Results of the simulation indicated that a family-wise error-corrected rate of $P < 0.05$ would be achieved with a voxel-wise threshold of $P < 0.005$ and a minimum cluster size of 132 voxels. Age, gender, and ethnicity (white, black, and other) were controlled in all analyses. All neural analyses are available on Neurovault (<https://neurovault.org/collections/4081/>).

Results

Behavioral results

To examine behavioral differences between the low-risk community and high-risk delinquent samples, we used SPSS (2017) to conduct a repeated-measures GLM with one within-subject variable (task condition: control, appetitive, aversive) and one between-subject variable (group: community, delinquent), while controlling for self-reported ethnicity, age, and gender. The effects of task ($F(2,74) = .128$) and group ($F(1,37) = 2.548$) were not statistically significant, but there was a significant condition-by-group interaction ($F(1,74) = 13.419$, $P < 0.001$, $\eta_p^2 = .266$). We used paired-samples t-tests to explore the group-by-task interaction effect (Figure 1). In the community sample, inhibitory performance in the control condition ($d'_{\text{Mean}} = 2.617$, $SD = 0.475$) was significantly better than in both the appetitive ($d'_{\text{Mean}} = 2.07$, $SD = 0.537$, $t(23) = 4.18$, $P < 0.001$, Cohen $d = 0.853$) and aversive condition ($d'_{\text{Mean}} = 2.299$, $SD = 0.541$,

Table 3. Neural regions that differentiate group (delinquent, community) and socioaffective condition (socially appetitive > socially aversive) linked to successful task performance

Region	t	k	x	y	z
mPFC	4.31	349	6	41	-11
R IFG	4.06	168	30	26	-11
L IFG	4.69	336	-42	35	-2
L TPJ	3.66	176	-45	-76	37
L cuneus	3.82	269	-12	-67	28
Brainstem	4.89	195	-6	-13	-17

Note. R refers to right and L refers to left; x, y, and z, to Montreal Neurological Institute coordinates; t, t-score at those coordinates (local maxima); k, number of contiguous voxels; IFG, inferior frontal gyrus; mPFC, medial prefrontal cortex; TPJ, temporal parietal junction.

[$t(23) = 2.884$, $P = 0.008$, Cohen $d = 0.589$]; additionally, inhibitory performance in the aversive condition was significantly better than in the appetitive condition [$t(23) = 2.079$, $P = 0.049$, Cohen $d = 0.424$]. Inhibitory performance patterns in the delinquent sample differed from the community sample. Specifically, inhibitory performance in the appetitive condition ($d'_{\text{Mean}} = 2.391$, $SD = 0.591$) was significantly better than in both the control ($d'_{\text{Mean}} = 2.017$, $SD = 0.567$, $t(23) = 3.747$, $P = 0.001$, Cohen $d = 0.765$) and aversive condition ($d'_{\text{Mean}} = 1.647$, $SD = 0.644$, $t(23) = 9.469$, $P < 0.001$, Cohen's $d = 1.932$); additionally, inhibitory performance in the control condition was significantly better than in the aversive condition ($t(23) = 3.318$, $P = 0.003$, Cohen $d = 0.678$). In short, the community sample showed greater inhibitory failures to appetitive cues, whereas the delinquent sample showed greater inhibitory failures to aversive cues. These findings suggest emotion-regulation difficulties for members of each group differ based on the socioaffective context, as the delinquent sample shows a different pattern of emotion regulation disruption compared to their community counterparts.

Neuroimaging results

Given that both behavioral profile and cue type produced a significant interaction effect on behavioral disruption, we next examined regions tied to successful task completion between groups. We conducted a two-sample (delinquent vs. community) whole-brain t-test comparing neural activation on the main contrast of interest (socially appetitive cues > socially aversive cues), using the PM for successful task completion relative to task failures. We observed significant group differences in the bilateral IFG, mPFC, TPJ, cuneus, and brainstem (Table 3). To understand the nature of interaction, we extracted parameter estimates from the IFG, mPFC, and TPJ clusters to unpack how these regions differentiated inhibitory success as a function of group and cue type. For descriptive purposes, we extracted parameter estimates of signal intensity from each group separately within the aversive and appetitive blocks. As shown in Figure 2, delinquent adolescents showed greater recruitment during successful inhibition toward socially aversive cues compared to community adolescents who showed greater recruitment during successful inhibition toward socially appetitive cues, suggesting that recruitment of these regions promoted successful task performance during the cue type where each group showed the most inhibitory failures. This suggests that the IFG, mPFC, and TPJ are involved in successfully inhibiting behavior in the presence of socioaffective cues; however, recruitment is not uniformly observed for all socioaffective cues but depends on the types of cues

that underlie emotion-regulation difficulties for each group. Looking solely within the control condition, we see significant activation differences in the posterior cingulate cortex; for the purposes of this article, focused on social cognition, we do not explore this further, although the analysis can be found on Neurovault (<https://neurovault.org/images/129030/>). Additionally, we conducted an exploratory seed-based functional connectivity analysis using the clusters of activation observed in the mPFC and the IFG. We conducted whole-brain connectivity analyses comparing the two groups using the gPPI toolbox in SPM (McLaren et al., 2012). We did not observe significant differences between the two groups in connectivity with either region that survived multiple-comparisons threshold correction.

Discussion

Adolescence is a transitory period, where social information takes on great importance for achieving age-specific goals (Nelson et al., 2016). The increased focus on socioaffective information guides attention toward cues that may signify a window of opportunity for adolescents to rise socially (Crone & Dahl, 2012). However, these opportunities for social advancement may also bear increased risk, and when neural reactivity is coupled with poor regulation, suboptimal outcomes may result (Casey, 2015). Previous research examining the effects of socioemotional stimuli on adolescents has shown that appetitive cues (Somerville et al., 2011; Perino et al., 2016) are linked with disinhibition at the behavioral and neural level in normative adolescent development. To extend this research to at-risk populations, we compared a community sample to a delinquent sample of adolescents to assess if these groups responded to socioaffective cues similarly (with the main distinction being one of magnitude where delinquent adolescents may show more difficulty with emotion regulation) or if these groups may respond differentially (with delinquent youth showing different patterns of emotion regulation difficulties). We found that the emotion regulation differences between community and delinquent adolescents were not entirely one of magnitude, as community adolescents showed greater difficulties in the presence of appetitive social cues, whereas delinquent adolescents showed greater difficulties in the presence of aversive social cues.

At the neural level, we observed that recruitment of the IFG, mPFC, and TPJ distinguished the groups. Delinquent adolescents showed significantly greater recruitment of these regions when successfully inhibiting their responses specifically in the presence of aversive cues, whereas the community sample showed greater recruitment in these regions when successfully inhibiting their responses in the presence of appetitive cues. These

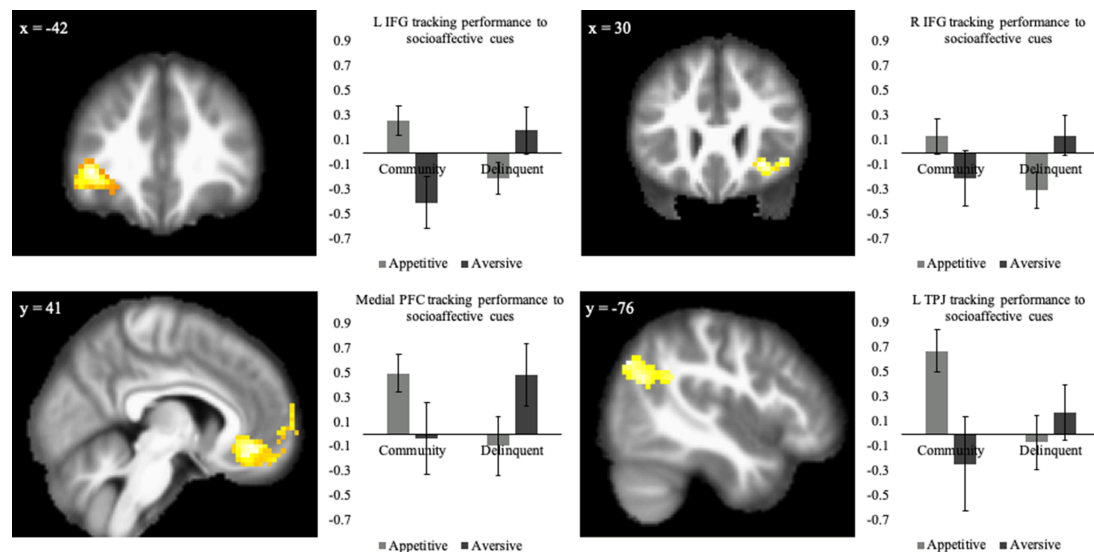


Fig. 2. Community and delinquent adolescents show differential tracking of successful inhibition in the left (L) and right (R) inferior frontal gyrus (IFG), medial prefrontal cortex (PFC), and left temporal parietal junction (TPJ). The y axis represents parameter estimates of signal intensity from neural regions that tracked with successful task performance. Positive numbers indicate increased recruitment in each region when successfully performing, whereas numbers around 0 indicate the region was not recruited as a function of task performance.

results suggest that while the same regulatory and social processing regions were recruited during the task, when they were recruited, they differed depending on the group (delinquent, community) and condition (aversive, appetitive). The inclusion of these regions is noteworthy, as they have been implicated in much of the developmental social neuroscience research examining adolescent cognition in social contexts (Hoorn *et al.*, 2019).

Interestingly, recruitment of the IFG and mPFC is greatest when it was most difficult for adolescents to complete the task without error. In particular, community adolescents showed the greatest behavioral disruption to appetitive socioaffective cues, which coincided with greater IFG recruitment, whereas delinquent adolescents showed the greatest behavioral disruption to aversive socioaffective cues, which coincided with greater IFG recruitment. The IFG has been consistently identified as a region implicated in inhibiting behavioral responses broadly (Swick *et al.*, 2008; Hampshire *et al.*, 2010), as well as tracking salient information and guiding attentional resources (Aron *et al.*, 2004; Menon & Uddin, 2010; Aron *et al.*, 2014). Hence, it is not surprising that the ability to focus on the go/no-go task while in the presence of affective stimuli was linked with IFG recruitment, as this would rely on inhibiting a disruptive affective response, focusing on task-specific instructions, and guiding attentional resources away from distracting cues.

The mPFC has been implicated in suboptimal adolescent decision making, specifically in relation to impulsivity (Dreyfuss *et al.*, 2014) and disruption related to affective stimuli (Dixon *et al.*, 2017). The mPFC is also linked with tracking errors during cognitive control (McCormick & Telzer, 2017), as well as negative feedback during risk taking (McCormick & Telzer, 2018), suggesting that the mPFC may be integral in decision making. Together, our findings suggest that the mPFC aids in monitoring errors and task-irrelevant information, as greater recruitment of this region corresponds to improved performance in conditions that the adolescents found the task most challenging. Ostensibly, the IFG and mPFC were recruited to regulate distracting cues and complete the task; however, when recruitment occurred, they differed between the adolescent groups depending on the socioaffective cues.

A similar pattern was found for the TPJ. The TPJ is implicated in many processes, including social cognition (Saxe, 2006). In adolescence, TPJ activation is tied to observing social cues (Burnett *et al.*, 2009) and is theorized to be integral in increases in social information processing observed in this time period (Nelson *et al.*, 2005). While some studies have linked increased TPJ activation with decreased risk taking (Guassi Moreira & Telzer, 2018) and increased prosocial decision making (van Hoorn *et al.*, 2016), others have implicated decreased recruitment of the TPJ in improved task performance (McCormick & Telzer, 2017), and it is consistently activated in adolescent decision making in social contexts (Hoorn *et al.*, 2019). Perhaps the recruitment of the TPJ in the current study is indicative of greater social information processing or attentional capture (Vossel *et al.*, 2014). Given that community adolescents needed greater regulatory recruitment during the appetitive condition—and vice versa for the delinquent adolescents—it would stand to reason that this recruitment was in response to the adolescents more fully processing cues in the given condition. As our results show, clarifying the role the TPJ plays in social information processing and how that impacts regulatory mechanisms is important in addressing (sub)optimal behaviors in adolescence.

The differential recruitment of regulatory and social information processing regions in this task suggests that delinquent and community adolescents may fundamentally differ in their processing of socioaffective cues. The presence of affective stimuli is irrelevant to the task behavior (i.e. each subject is supposed to either press or inhibit their response to the letter stimuli, regardless of the background image); however, our results highlight that task-irrelevant affective information can have an outsized role for adolescents. While models of adolescent brain development have postulated that individual difference factors (such as life history and environmental context) likely alter how socioaffective and regulatory systems evolve (Nelson *et al.*, 2016), such positions until recently have been mostly theoretical (Foulkes & Blakemore, 2018; Lee *et al.*, 2018; Perino *et al.*, 2019).

Our research highlights that while emotional stimuli may be problematic across adolescence, the effect is not uniform and is distinguishable when accounting for behavioral characteristics.

Community adolescents had problems with appetitive stimuli—perhaps reflective of disruption in approach to the presence of prosocial cues—while delinquent adolescents had problems with aversive stimuli—perhaps reflective of disruption toward threat or environmental instability, which may be more prevalent in their daily lives (Agnew, 1992; Ellis et al., 2012). Our task utilized emotional stimuli to indirectly capture attention, requiring adolescents to engage regulatory processing to redirect the adolescent (e.g. the distracting effect of emotion). Tasks that require more explicit focus on emotional stimuli for task completion, such as reading emotional cues, likely invoke different psychological processes (Lee et al., 2019; McCormick et al., 2018), a distinction that may be particularly useful for pinpointing when delinquent adolescents differ from their low-risk counterparts. Historically, studies examining adolescents with conduct issues have observed a broad pattern of physiological hypoactivity (as measured by heart rate, galvanic skin response, eye-blink startle, and neuroimaging studies) to negatively valenced stimuli (Blair et al., 2016). The findings presented in this study suggest future research should examine how socioaffective information may be incorporated into decision-making processes irrespective of physiological responsivity, as emotional stimuli are likely to impact behavior even if it does not impact autonomic functioning. Our results provide preliminary evidence to the hypothesis that behavioral profiles may undergird neurodevelopment, as the past behavior of adolescents was related to both when they were likely to be distracted by affective stimuli, and when the same neural regions were recruited to successfully regulate behavior.

We found that past delinquent acts were a meaningful variable for understanding emotion regulation, as we saw differential neurobehavioral responses. High-risk adolescents' problematic behaviors may be tied to adapting to aversive social cues and contexts, which suggests that assessing the contextual information surrounding past behavior may be integral to understanding delinquency and sharpening future research inquiries. Disinhibition, in and of itself, is not a universally problematic phenomenon, as acting quickly in response to seeing opportunities for rewarding social gains or threatening contexts may sometimes be beneficial. As the field of developmental neuroscience progresses, the need to apply our findings within the greater context of varying social structures becomes more pertinent (Casey et al., 2016). In order for empirically based findings to best inform potential interventions aimed at addressing social problems, it is imperative that we base our results on samples actively engaged in the problems we want to tackle (e.g. delinquency) in relevant situational contexts. Our study suggests that ancillary socioaffective cues are likely to be particularly distracting in adolescence. Future work ought to tackle how disinhibition to varying social stimuli may directly (or indirectly) connect to substance use and antisociality, as the relationship between social disinhibition and antisocial behaviors occurring due to psychopathology is currently not well elucidated. Exploring if these suboptimal outcomes are driven by, or orthogonal to, socially provoked disinhibition will be of great importance for future research.

While this study represents an important step toward understanding how individual difference factors need to be accounted for in developmental neuroscience, there are limitations that require future attention. First, because we used a cross-sectional design, we did not explore the progression of emotion regulation in adolescents, which limits our ability to developmentally answer how regulatory ability changes due to learned experience (Agnew, 1992; Ellis et al., 2012). It is possible that such experiences

may alter how individuals perceive socioaffective stimuli in future interactions, a concern we are unable to address in the current study. Future research should examine how individual difference factors (such as behavioral history) alter trajectories of affective perception and the progression of emotion regulation difficulties. By applying both prospective and retrospective analyses that tie neural development to meaningful behavioral differences, researchers may gain insight into critical intervention periods. Future research examining how the development of social cognition is impacted by behavior and the environmental inputs, as well as how that might cascade into the neurodevelopment of regulatory processing, is of the most importance.

Second, while the distinction between adolescents who offend and those who do not has been shown to be quite meaningful (Cohen & Piquero, 2009; Cohen et al., 2010; Moffitt & Caspi, 2001), this assessment is somewhat blunt and oftentimes open to class, gender, and race biases (Wald & Losen, 2003). We attempted to mitigate this concern by selecting a gender- and race-balanced cohort for our high-risk delinquent sample that was from the same region as our community sample, but we recognize that not all acts receive the same type of discipline and that not all disciplinary actions are inherently just or represent equivalently severe transgressions. We believe verifiable evidence of a disciplinary act would be a useful starting point but recognize the need for greater specificity of transgression in future endeavors. While having a continuous measure of verifiable acts of delinquency would be ideal for such a study, verifying such information without secondary sources (e.g. school, police, and social services records), clinical assessments, and parental input is quite difficult. There have been calls for greater specificity and standardization when assessing delinquency, such as focusing on intent, motivational factors, and specific behaviors present in delinquent acts (Welner et al., 2018); perhaps this is an avenue the field can proceed down to improve the precision of our findings to the detrimental behaviors delinquent populations may engage in. Quantifying delinquent acts on a number of continuums will allow for greater precision in explaining physiological differences and targets for intervention in future research.

Third, we did not have clinical assessments or other measures aimed at delinquency collected in both groups; future work should incorporate both verifiable evidence and a wide assay of individual difference factors, as variations in social motivation, perceptual processing, and lived experience are theorized to explain much of when and why adolescents focus on socioaffective stimuli (Nelson et al., 2016). There is a large body of research focusing on externalizing and aggression (see Blair et al., 2014; Blair et al., 2016; Viding & McCrory, 2012) that has by proxy examined delinquent behavior via clinical populations. While certainly valuable, this research base may not be dispositive toward understanding normative increases in adolescent risk taking and how that can result in suboptimal outcomes in nonclinical samples. Part of the complication is that much of the aforementioned research focuses on deficiencies in offending youth (Bjorklund & Hawley, 2014). Focusing on antisocial behaviors versus psychometrically assessed constructs associated with antisociality provides different information that may muddy how we understand delinquency and offending populations (Hyde et al., 2013). Given that research into hierarchical approaches of psychopathology has found that delinquent outcomes are tied to both general dysfunction (the p-factor) and externalizing syndromes (Caspi et al., 2014), measurement issues and outcome convergence need to be thoughtfully addressed in future research (Watts et al., 2019). Future research into

adolescent risk taking ought to focus more on recruiting delinquent samples, increased collection of demographic and individual difference variables, and providing as much contextual information regarding past behavior as feasible. Many studies, including this one, are limited by their sample size and time requirements to get fine-grained assessments across individual differences.

Our results help to shed light on the process of successful emotion regulation in adolescents, as well as provide a window into how prior behavior may inform when and why adolescents are likely to engage in specific types of suboptimal decision making. The cues that lead adolescents without prior histories of delinquency astray may not be equivalent for adolescents already engaging in delinquent acts. Emotion regulation difficulties across different adolescents are specific to both behavioral history and social context, and research surrounding how to best understand and ultimately intervene upon problematic adolescent outcomes ought to account for this discrepancy. This study provides a useful comparative analysis, showing that emotion regulation failures seen across adolescence require accounting for behavior profile, as community adolescents' emotion regulation difficulties were qualitatively different from delinquent adolescents.

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