# Incorporating the social context into neurocognitive models of adolescent decision-making: A neuroimaging meta-analysis

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## Abstract

Neurobiological models of adolescent decision-making emphasize developmental changes in brain regions involved in affect (e.g., ventral striatum) and cognitive control (e.g., lateral prefrontal cortex). Although social context plays an important role in adolescent decision-making, current models do not discuss brain regions implicated in processing social information (e.g., dorsomedial prefrontal cortex). We conducted a coordinate-based meta-analysis using the Multilevel peak Kernel Density Analysis (MKDA) method to test the hypothesis that brain regions involved in affect, cognitive control, and social information processing support adolescent decision-making in social contexts (N = 21 functional neuroimaging studies; N = 1292 participants). Results indicated that dorsomedial prefrontal cortex, inferior frontal gyrus/insula and ventral striatum are consistently associated with adolescent decision-making in social contexts. Activity within these regions was modulated by the type of social context and social actors involved. Findings suggest including brain regions involved in social information processing into models of adolescent decision-making. We propose a 'constructionist' model, which describes psychological processes and corresponding neural networks related to affect, cognitive control, and social information processing.

## 1. Introduction

Many decisions in a teenagers' life affect or are influenced by other people. For instance, the decision to speed through a yellow light with a risk-endorsing friend in the car can affect the safety of the driver, the friend, and the adolescents' relationships with their parents. Yet, speeding through a yellow light may also enhance a teen's social status with their friend, potentially making it worth the consequences. The work of developmental neuroscientists

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seeks to understand how these everyday instances of decision-making in social contexts unfold in the developing brain.

Adolescence is a time of heightened risk-taking behaviors and increased social-affective sensitivity. These processes occur in parallel with tremendous changes in the developing brain. Prominent neurobiological models of adolescent behavior emphasize adolescents' orientation towards rewards and risk-taking and thus focus on the developmental changes that occur within neural networks implicated in affective sensitivity (e.g., ventral striatum; VS) and cognitive control (e.g., lateral prefrontal cortex; Steinberg, 2008; Shulman et al., 2016; Casey et al., 2008; 2015). Yet models of decision-making in adolescence do not take into consideration the important role of neural regions involved in social information processing (e.g., dorsomedial prefrontal cortex, temporo-parietal junction), despite the fact that adolescents show uniquely heightened activation within these regions in response to social information (e.g., Blakemore, 2008; Blakemore & Mills, 2014; Nelson et al., 2005; 2016). In the present work, we underscore the greater need to focus on the social context when examining adolescent decision-making. We perform a coordinate-based quantitative meta-analysis to examine whether brain regions involved in social information processing are involved during adolescent decision-making in social contexts. We close by proposing a 'constructionist' model of adolescent decision-making that models psychological processes and corresponding neural networks related to affective salience, social information processing, and cognitive control.

## 1.1 Heightened risk-taking and social-affective sensitivity in adolescence

To date, important scientific advances in our understanding of adolescent neurocognition have been guided by separate neurobiological models that describe adolescents' heightened sensation seeking and social-affective sensitivity. The *Dual Systems Model* (Steinberg, 2008; Shulman et al., 2016) and *Imbalance Model* (Casey, 2008; 2015) suggest that adolescents demonstrate heightened activation in the affective system (e.g., ventral striatum (VS), insula, amygdala) at a developmental period of vulnerability when the cognitive control system (e.g., lateral PFC) is not yet mature (also see Romer, Reyna, & Satterthwaite, 2017; Li, 2017 for recent adaptions of these models). Heightened affective sensitivity paired with an inability to engage in effective regulation, is thought to result in an orientation towards rewards and greater risk-taking behavior. Early fMRI studies support these models, demonstrating unique VS sensitivity to rewards among adolescents compared to children or adults (for review of this seminal work, see Galvan, 2010) as well as altered activation during regulatory tasks in the prefrontal cortex (for review see Crone & Dahl, 2012). Although recent studies have continued to provide empirical support for differential activation of affective and cognitive control networks during adolescence (e.g., Barkley-Levenson & Galvan, 2014; Braams et al., 2014; Van Duijvenvoorde et al., 2016; Van Leijenhorst et al., 2010; Qu, Galvan, Fuligni, Lieberman, & Telzer, 2015; for a meta-analysis see Silverman, Jedd, & Luciana, 2015), there has also been a call for a more nuanced understanding of interactions across brain regions involved in cognitive, affective, and social processing (Pfeifer & Allen, 2016; Crone & Dahl, 2012).

Much of the existing research on the neurodevelopment of adolescent decision-making has been conducted in a social vacuum. Yet in daily life, adolescent decision-making often occurs in the context of peers, parents, or other important social agents who may impact decisions (Albert et al., 2013; Blakemore & Mills, 2014; Schriber & Guyer, 2016). Compared to children, adolescents spend more time with peers, form more sophisticated and complex social relationships, are more sensitive to peer acceptance, and become more self-conscious (Brown, 2004; see Blakemore & Mills, 2014). Indeed, adolescents show uniquely heightened embarrassment when being watched by their peers (Somerville et al., 2013) and have compromised emotion regulation compared to children or adults in the presence of socially appetitive cues (Somerville et al., 2011). In addition, among adolescents, a greater orientation towards rewards and greater risk-taking behaviors are more likely to occur in a social than non-social context (Albert et al., 2013; Steinberg et al., 2017; Duckworth & Steinberg, 2015). For example, adolescents are more susceptible to risk-taking than adults in the presence of peers (Gardner & Steinberg, 2005) and tend to conform to the attitudes of their peers about risky behaviors more so than adults (Knoll et al., 2015). As such, it has been proposed that adolescence is a uniquely sensitive period for sociocultural information processing (Blakemore & Mills, 2014).

Because adolescent decision-making is most likely to occur in a social context, neurobiological models of adolescent decision-making could benefit by incorporating neural regions that support social information processing. According to models of social cognition, and the *Social Brain Model* (Blakemore, 2008) in particular, information from the social context is processed by a collection of regions that support the ability to mentalize such as the dorsomedial prefrontal cortex (dmPFC), temporo-parietal junction (TPJ), and posterior superior temporal sulcus (pSTS) (Blakemore, 2008; Blakemore & Mills, 2014; Mitchell, Macrae, & Banaji, 2005; Spunt & Lieberman, 2013; Saxe, 2006; Van Overwalle, 2009). Mentalizing involves recognizing that another person has a mind, thinking about another's thoughts and feelings, and predicting another's behavior to guide one's own decisions (Waytz, Gray, Epley, & Wegner, 2010). The literature consistently shows functional changes in these social brain regions across development. In particular, adolescents show greater mPFC activity during mentalizing tasks than adults (Blakemore et al., 2007; Burnett et al., 2009; Gunther Moor et al., 2012; Pfeifer et al., 2009; Van den Bos et al., 2011; Wang et al., 2006, Somerville et al., 2013). For example, relative to adults, adolescents show greater mPFC activation when thinking about intentions (Blakemore et al., 2007). These findings underscore adolescence as a key period of social sensitivity (Blakemore, 2008; Blakemore & Mills, 2014).

## 1.2 Social context and adolescent decision-making

Surprisingly, social context has remained an elusive construct throughout the developmental neuroimaging literature. A wide range of social contexts have been studied without the broader concept being explicitly defined. Here, we define decision-making in a *social context* as decisions in which others are involved. We aim to understand neural activity specifically related to *decision-making in a social context*. To refine the construct of social context, we distinguish between social processes that affect the input for a decision versus the outcome of a decision. As such, we define two types of decisions in a social context: 1)

those in which the decision-maker is affected by others (i.e., *social influence decisions*) and 2) those in which an individual's decisions affect others (i.e., *social outcome decisions*). Note that other social processes such as social emotion processing, face processing or receiving peer evaluation are other crucial processes that develop during adolescence (Blakemore & Mills, 2014), but these processes have not been studied in the context of decision-making per se, and as such are not examined in this meta-analysis. Given the social reorientation that occurs during adolescence, both social influence and social outcome decisions are common and highly salient in adolescents' daily lives (Blakemore, in press; Nelson et al., 2005; 2016). We expect social influence and social outcome decisions to be moderated by *social actors,* or who adolescents are interacting with in the moment (Telzer, van Hoorn, Rogers, & Do, 2018).

**1.2.1    Social influence decisions.—**Social influence decisions occur when adolescents' behaviors or attitudes are explicitly or implicitly influenced by others, such as friends, the larger peer group or family (Brechwald & Prinstein, 2011; Telzer, Van Hoorn, Rogers, & Do, 2018). This may include very explicit social pressure, such as friends being present and egging on an adolescent to drink or drive fast, or online social media websites that use 'likes' as quantifiable social endorsements (e.g., Instagram, Facebook). Through such explicit feedback, the peer group reinforces social norms, which in turn may guide subsequent decisions (Brechwald & Prinstein, 2011). Social influence can also be more implicit and guided by the (mis)perception of social norms, such as thinking one's peers drink a lot, leading to greater substance use (Prinstein & Wang, 2005; McDonald & Crandall, 2015). As such, an adolescent may adapt their decisions to conform to perceived social norms to gain social approval and connection with others (DeWall & Richman, 2011). This implied "psychological presence" of others can lead to mentalizing about others' goals, values and expectations, and influences subsequent behavior (Shah, 2003).

**1.2.2    Social outcome decisions.—**Social outcome decisions denote instances when the outcome of one's decisions affect other people. In the risk-taking domain, adolescents' decisions often not only affect themselves but close others as well. For instance, taking their parents' car for a joy ride can result in being grounded (personal risk), crashing the car (financial risk to the family), or sacrificing their friend's safety if they were in the car together (Guassi Moreira & Telzer, 2018b). Social outcomes could also be more abstract, such as angering parents, offending friends or hurting one's social standing. In the prosocial domain, social outcome decisions can include fairness considerations, strategic bargaining, trust, reciprocity, and prosocial behaviors (Crone, Will, Overgaauw, & Guroglu, 2012). For example, an adolescent may offer help to a friend who is sad or struggles with homework, or reciprocate someone else's trust. Among these different social decisions, each requires the need to draw an inference about the mental state of another person (Lee & Harris, 2013).

**1.2.3    Social actors.—**Adolescent decision-making in social contexts (i.e., social influence or social outcome decisions) is likely dependent on several factors, including *who* adolescents are interacting with (i.e., the social actors). Oftentimes experimental paradigms involve anonymous others to carefully control for previous experiences or potential beliefs that may be attributed to known others. However, previous work also suggests that decision-

making may change depending on the beneficiary. For example, adolescents are more prosocial towards friends than anonymous others (Guroglu et al., 2014; Padilla-Walker, Carlo, & Memmott-Elison, 2017) and alter their risky decisions when they affect themselves or their family (Guassi-Moreira & Telzer, 2018b). Moreover, while peer rejection has been linked to greater risk-taking behaviors such as substance use (Prinstein & La Greca, 2004), supervision by parents is associated with lower levels of risk-taking (Borawski, Ievers-Landis, Lovegreen, & Trail, 2003). Together, this work highlights that the type of social actor can moderate adolescent decision-making in social contexts, and likely the recruitment of neural regions representing information about the social context.

### 1.3 Present study

Despite the importance of the social context, neurobiological models of adolescent decision-making have not explicitly incorporated regions representing the social context. We took a data-driven, quantitative approach to test the hypothesis that brain regions involved in affect, cognitive control, and social information processing support adolescent decision-making in social contexts. In order to do so, we performed a coordinate-based quantitative meta-analysis on the existing developmental neuroimaging literature. Meta-analysis is advantageous because it summarizes the set of brain regions that show *consistent* (i.e., reliable) increases in activation across a range of studies (Kober & Wager, 2010). The set of brain regions that are consistently activated during a certain class of studies are referred to as a "neural reference space" and represent the brain regions that are probabilistically more likely to show increased activation during the process of interest as compared to chance (Barrett et al. 2007; Lindquist et al. 2012; Wager et al., 2007). Meta-analysis can also demonstrate brain regions that are more likely to be involved in one experimental condition versus another, and thus can speak to the relative specificity of neural function. Neuroimaging studies are prone to Type-I error due to small sample sizes and may lack generalizability because single studies can only assess a few conditions (Wager et al. 2007). Meta-analysis is thus ideal to generate data-driven hypotheses (cf. Pfeifer & Allen, 2016), through summarizing data from multiple studies.

Our main goal was to examine the neural reference space associated with decision-making in a social context during adolescence. Based on existing neurobiological models of decision-making and social cognition, we expected that the neural reference space associated with adolescent decision-making in social contexts would encompass brain regions associated with affective (i.e., VS, insula, amygdala), cognitive control (lPFC), and social information processing (dmPFC, TPJ) (Blakemore, 2008; Blakemore & Mills, 2014; Casey, 2008; 2015; Nelson et al., 2016; Smith et al., 2014; Steinberg, 2008; Shulman et al., 2016). These affective, cognitive, and social brain regions are part of complex and dynamically interacting neural networks (Casey, 2015). While taking a functional connectivity or network-approach is certainly insightful (e.g., see McCormick, van Hoorn, Cohen, & Telzer, 2018), most individual studies and meta-analytic techniques to date allow for assessing consistent mean levels of activation only. As such, this is our focus in the current work.

Next, we examined how the neural reference space is modulated by characteristics of the social context. In particular, we disentangled effects of social context type by comparing

neural activation consistently associated with social influence decisions versus social outcome decisions. We also built on growing research examining effects of social actors (Guassi-Moreira & Telzer, 2018b; Guroglu et al., 2014; Padilla-Walker et al., 2017; Prinstein et al., 2001) by comparing the neural reference space when social actors were known versus unknown others.

## 2. Methods

### 2.1 Database

The database for the meta-analysis included 21 empirical functional neuroimaging studies of adolescent decision-making in a social context ($N = 1292$ total participants; 61 contrasts and 331 data points (peak coordinates)) published between 2011 and June 2017. As a follow up, we searched websites of research laboratories that conduct fMRI research on relevant topics to ensure that our search encompassed the most recent papers. A final literature search was conducted by independent researchers and yielded no additional papers. As such, the database represents all studies of adolescent decision-making in social contexts that met our inclusion criteria until the stop-point for data collection for this project.

Using scholarly search engines such as PsycInfo, PubMed and Google Scholar, we sampled papers based on specific search criteria: our targeted measurement (e.g., "fMRI"), our target sample type and age (e.g., "human," "adolescence/adolescents"), overall area of research or phenomenon (e.g., "social influence," "social evaluation," "social decision-making," "social context," "peer influence," "parental influence," "risk-taking," "risky behavior," "social (peer) exclusion," "peer feedback"), and specific tasks that are typically used in this literature (e.g., "family donation task," "trust game," "prisoner's dilemma," "reward tasks," and "ultimatum game"). Our initial search was broad, in order to be inclusive and to ensure that our codes represented the full range of tasks used in the literature. We did not restrict our search from a particular start date, but reflecting the novelty of this field, the earliest eligible study in our database was published in 2006. Our initial literature search produced 82 papers, including literature reviews and meta-analyses on separate topics in developmental neuroscience. Following the initial search, 30 papers were excluded that did not have social context or were literature reviews or meta-analyses; 17 additional papers were excluded due to tasks that we considered unrelated to our phenomenon of interest (i.e., Cyberball) and 14 papers were excluded as they used methods or analyses that are not currently compatible with our analysis method (e.g., functional connectivity analyses; longitudinal analyses), resulting in a final sample of 21 papers.

**2.1.1 Inclusion and exclusion criteria.**—Only fMRI tasks involving *decision-making* were included. Social feedback processing (receiving social rejection or acceptance from peers; e.g., a Chatroom Task) and outcome processing (e.g., a task analyzing neural responses to reward but not decision-making) were beyond the scope of the current meta-analysis, as they did not explicitly model decision-making. Cyberball and similar tasks (e.g., Chatroom) were excluded because we considered receiving explicit social rejection to be a different phenomenon from the more subtle social decision-making we were interested in. Since our goal was to specifically focus on social influence and social outcome decisions,

we did not include non-social decision-making studies as the set of non-social decision-making studies is quite large and diverse in respect to the types of decision-making tasks/procedures included. See Table 1 for an extensive overview of studies including tasks employed, coding for social context categories (social influence decisions, social outcome decisions, other) and social actor type (known other, unknown other), contrasts included, as well as other dimensions of interest such as sample size.

We focused on studies in the adolescent age range, defined as ages between 10–22 years (Steinberg, 2008). To ensure that we had ample power and were inclusive, we included a slightly wider age range (ages 8–26 years) in our final database. To balance concerns about power with those about validity, papers including a wider age range were only included when the majority of participants fell within the adolescent age range (e.g., Braams & Crone, 2016 with only a few participants on the youngest and oldest ends of the age range (ages <10 years and > 22 years)) and when papers directly compared adolescents to adults or children; papers exclusively assessing adults or children were excluded. Importantly, each of the papers included had a mean age within the traditional age range of adolescence, with a collective mean age (*SD*) of 15.80(0.62). All studies included healthy, typically developing participants and excluded patient samples. We did not explicitly search for patient populations, but examined all studies that qualified within our criteria, and have been inclusive of all papers we could identify. Prior meta-analyses excluded contrasts that focus on comparing specific groups of participants (e.g., overweight v. healthy weight) but we chose to retain three studies that contrasted specific groups within their sample. We retained these papers to ensure power and err on the side of inclusion because none included an exclusively patient-based sample (Telzer et al., 2017: chronically victimized and non-victimized; Van den Bos et al., 2014: antisocial (some of them diagnosed) and typically developing controls; Verdejo Garcia et al., 2015: excess weight and normal weight). Analyses with and without these studies yielded no substantial differences (for more details, see the neural reference space section below).

We also excluded studies that utilized methods or analyses not compatible with the nature of our meta-analytic technique, the Multilevel Peak Kernel Density Analysis (MKDA; for technical details see section 2.2). Group-level longitudinal findings were not included as they track brain changes over time within the same individuals rather than assessing brain processes within individuals at a specific point in time, like all cross-sectional findings included. If data from each time-point was provided in a longitudinal study, only the first time-point was added to the database as a singular data point (example: Braams & Crone, 2016). If multiple studies reported different analyses on the same sample, we did not include those findings twice, as they would be non-independent. An exception to this rule was Braams & Crone (2017), as the task employed was slightly different between studies. In all other cases, a study with whole-brain analyses was preferred over a study with region of interest analyses (e.g. Telzer et al., 2011 included, Telzer et al., 2010 excluded).

Finally, this meta-analysis was limited to contrast analyses reported in each study and if information was not clearly reported in the paper, we reached out to the first authors for additional information. Studies reporting percent signal change (e.g. Smith et al., 2015), parametric analyses, individual differences analyses (e.g., Pfeifer et al., 2011 correlations

with the Resistance to Peer Influence questionnaire), psychophysiological interactions (PPI) analyses (e.g., Somerville et al., 2013 mPFC-striatum connectivity), and network analyses could not be included as the MKDA only summarizes reported peak activations from study-level experimental contrasts. As a result, not all studies with relevant findings are included in this quantitative meta-analysis. In Supplementary Table 1 we describe excluded studies and reasons for exclusion.

**2.1.2 Coding.—**Each study contrast was coded on a number of dimensions by two researchers (JVH and HS), including sample size, gender ratio, category of social task and social actor type. Any disagreements between the two researchers were resolved through discussion and a third individual (EHT).

Tasks involving social influence decisions, i.e., when decisions are impacted by others, included both tasks with explicit feedback on behavioral choices provided by others (e.g., Van Hoorn et al., 2016), as well as more subtle forms where people were observing decisions (e.g., Chein et al., 2011), ranking how well adolescents do relative to others (e.g., Op de Macks et al., 2016), and social manipulations such as priming social exclusion before partaking in risk-taking behaviors (e.g., Peake et al., 2013).

Tasks involving social outcome decisions, i.e., making decisions in which outcomes affect others, have been studied most often using economic games that involve some kind of distribution of tokens or points. Tasks that fall within this category include the Trust Game (e.g., Van den Bos, 2011), Ultimatum Game (e.g., Steinmann et al., 2014), Dictator Game (e.g., Gunther Moor et al., 2012), and Family Donation Task (e.g., Telzer et al., 2011). Moreover, some previous work has manipulated the social context in risk-taking paradigms by specifying that the outcomes of decisions would affect others; we also included these types of studies (e.g., Braams & Crone, 2016).

Finally, two studies that did not neatly fall within either of these categories (social go-nogo; Perino et al., 2016; risky vs neutral decisions with a peer; Rodrigo et al., 2014) were classified as "other" social tasks. These contributed to the overall neural reference space but were not included in analyses specifically examining social influence decisions or social outcome decisions.

Some prior behavioral research suggests that social relationships may differentially modulate behavior and neural activity, especially when interacting with known others relative to unknown others (Guassi-Moreira & Telzer, 2018ab; Guroglu et al., 2014; Padilla-Walker et al., 2017; Prinstein et al., 2001). Thus, we also coded studies based on the type of 'social actor', which refers to who the other individual is that the participant is either playing for, against, or is aware exists and is observing.

## 2.2 An Overview of Multilevel Peak Kernel Density Analysis (MKDA)

The meta-analysis examines reported peak coordinates across the brain using Multilevel peak Kernel Density Analysis (MKDA; Wager et al., 2007; Kober & Wager, 2010) in Neuroelf (http://neuroelf.net). MKDA groups peaks within a single contrast and creates contrast maps for each, using study (or independent contrasts in a study if multiple contrasts

are reported in a single study) as an overall unit of analysis. In typical neuroimaging meta-analyses coordinates are convolved with spheres ranging between 10mm and 15mm (for data-driven evidence see Salimi-Khorshidi et al. 2009); building off of prior research that has specifically used the MKDA procedure (Kober et al., 2008; Kober & Wager, 2010; Lindquist et al. 2016; Brooks et al., 2016; Wager et al., 2007), coordinates from each contrast were convolved with 12-mm spheres to create binary comparison indicator maps. Since study contrasts are the main units of analysis, to prevent any single study from biasing the results (due to many peaks, more liberal thresholding, or statistical power), the indicator maps were then weighted depending on the type of analyses used (fixed or random) and the sample size of the contrast. This approach allows the MKDA to control for differences in the quality of the data entering the meta-analysis due to the reliability of the statistical analyses used or the sample size.

Specifically, following previous meta-analyses (Brooks et al., 2016; Lindquist et al. 2012; Lindquist et al., 2016), studies were weighted by the square root of sample size and studies with fixed effects were down-weighted by .75, resulting in studies with higher sample sizes having more influence, and fixed effects having less (for in depth explanation, see Kober et al., 2008; Kober & Wager, 2010; Lindquist et al., 2012, Wager et al., 2007). Note that there were no studies in the current database that used fixed effects analyses. The resulting meta-analytic contrast maps are then created based on the proportion (i.e., density) of contrasts activating near any given voxel. This proportion is thresholded by comparing it to a null distribution created through Monte Carlo simulations that compute the likelihood of finding any activation in any voxel within gray matter (excluding white matter).

We first examined the overall neural reference space across all studies of adolescent decision-making in social contexts, i.e., the brain areas that show consistent activation that is greater than would be expected by chance across all studies in our database. Five thousand Monte Carlo simulations were performed, and following our prior work (Lindquist et al. 2012; 2016) only voxels surpassing a stringent height-based threshold of $p < .01$ were considered significant. Practically, this means that the findings observed to be consistent across all studies in the literature would have been found by chance only 1% of the time. Resulting maps were cluster-level thresholded using a family wise error rate of $p < .05$.

Following the computation of the neural reference space, we then computed a series of meta-analytic contrasts assessing how characteristics of the social context modulate neural activation (discussed in more detail below). These meta-analytic contrasts created binary comparison indicator maps of the respective study-level contrasts that were then compared to a null distribution created through Monte Carlo simulations. Again, voxels surpassing the height-based threshold of $p < .01$ were considered significant. In one meta-analytic contrast in which there were no voxels that surpassed this more stringent threshold, we report exploratory findings at a more lenient threshold ($p < .02$). We opt to do so given the relatively small sample size in this relatively new literature; exploratory results should be interpreted in the context of discovery for future work. Resulting maps were cluster-level thresholded using a family wise error rate of $p < .05$.

### 2.3    Analysis plan for testing the neural reference space of adolescent decision-making in social context

**2.3.1    Neural reference space.—**In our key analysis, we sought to examine the neural reference space for adolescent decision-making in a social context across different tasks and domains. The neural reference space contains consistent increases in brain activation during decision-making in a social context that occurs more frequently than would be expected by chance across the literature. To ensure that specific studies/samples included did not unduly bias our findings, we ran this analysis with both a full and a more conservative version of the database. First, we included all studies from our database (21 studies, 61 contrasts and 331 data points). Second, we ran two more conservative analyses. The first excluded contrasts that contained age comparisons (from Van den Bos et al., 2011; Chein et al., 2011; Rodrigo et al., 2014; Steinmann et al., 2014; Gunter Moor et al., 2012), resulting in 52 contrasts, 19 studies and 298 data points. The second additionally excluded contrasts from three studies that contained comparisons amongst groups (e.g., chronically victimized v. non-victimized adolescents) within their sample (Van den Bos et al., 2014; Telzer et al., 2017; Verdejo-Garcia et al., 2014), resulting in 47 contrasts, 18 studies and 264 points. Findings from both of these more conservative neural spaces were largely identical to the larger neural reference space, thus we included all studies in subsequent meta-analytic contrasts to retain power and more fully characterize the literature. We report the findings from the more conservative reference spaces in the supplementary material[1].

**2.3.2    Social Context Type.—**To examine the influence of the type of social context (social influence v. social outcome decisions), we next conducted a series of targeted meta-analytic contrasts. For contrasts included from each study, please see Table 1.

Our meta-analytic contrasts compared task types: (1) social influence decisions versus all other social tasks, and (2) social outcome decisions versus all other social tasks. This allowed us to disentangle the brain regions associated with these two different categories of social contexts. Here, we also ran a more constrained analysis where we excluded the two 'other' social context studies (Perino et al., 2016; Rodrigo et al., 2014), resulting in 56 contrasts, 19 studies, and 261 data points. The findings with the unconstrained meta-analytic contrast were again largely identical, thus we included the other studies to retain power.

**2.3.3    Social Actor Type.—**Finally, to gain more insight into the effects of different social actors on neural activity, we examined potential differences based on social actor type. In order to do so, we conducted a meta-analytic contrast comparing across all tasks whether they involved known others (e.g., family members, known peers) versus unknown others (e.g., peer confederates, unknown adult), as well as the reverse meta-analytic contrast unknown others versus known others.

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[1]We report findings from the more conservative neural reference spaces thresholded at $p < .01$ and $p < .02$ in the supplement. The insula/IFG effect does not reach significance at our determined threshold of $p < .01$, but is visible at $p < .02$, which suggests this is a power issue rather than the studies adding in qualitatively different data.

## 3.   Results

### 3.1   Neural reference space of adolescent decision-making in social contexts

As predicted, the neural reference space for adolescent decision-making in social contexts showed that decision-making in social contexts elicits activation in brain regions implicated in affective sensitivity (bilateral VS, insula), cognitive control (IFG), but also social information processing (dmPFC extending into mPFC) (see Figure 1; Table 2).

**3.1.1   Social Context Type.**—For social influence decisions > all other social tasks, there were no significant effects at our conservative a priori threshold of p<.01. Given the novelty of the database and the relatively small sample of studies included, we thus report exploratory analyses at a less stringent threshold. At the threshold of $p < .02$, we found a cluster of regions implicated in social information processing that encompassed inferior parietal lobule (IPL), temporo-parietal junction (TPJ), and posterior superior temporal sulcus (pSTS) (see Figure 2A; Table 3). These exploratory findings should be interpreted in the context of discovery for future research, although it is notable that they are consistent with *a priori* predictions that regions involved in mentalizing would be active when making decisions in the presence of social others. For social outcome decisions > all other social tasks, we observed a large cluster in the VS, which highlights the rewarding/salient nature of making decisions where the outcome affects others (see Figure 2B; Table 3).

**3.1.2.   Social Actor Type.**—Known others > unknown others elicited activity in bilateral VS (See Figure 2C; Table 3). For the reverse contrast, unknown others > known others, we observed activation in the subgenual ACC extending into the amygdala as well as the right postcentral gyrus (See Figure 2D; Table 3).

## 4.   Discussion

Adolescence is a time when the social world is particularly salient (Blakemore, in press), and decision-making is especially influenced by social information in emotionally-charged 'hot' social contexts (Duckworth & Steinberg, 2015). The goal of the current meta-analysis was to investigate the neural bases of adolescent decision-making in social contexts across the emerging developmental neuroimaging literature. Recent adaptions of neurobiological models of adolescent risk-taking acknowledge the important role of the social context (e.g., Shulman et al., 2016), but the discussion of the underlying neural circuitry involved in adolescent decision-making has yet to expand beyond brain networks implicated in affective sensitivity and cognitive control (Pfeifer & Allen, 2016). Our results provide meta-analytic evidence that VS, insula/IFG, and dmPFC are consistently implicated in adolescent decision-making in social contexts. These findings support the notion that it is crucial to move beyond the popular notion of dueling affective and cognitive control systems in order to gain traction on understanding adolescent neurocognition. Our findings underscore the fact that studies of developmental social-affective processes must measure and model psychological and neural processes related to affect, cognitive control, *and* social information processing, taking into account not only the developmental window during which processes are occurring, but also the momentary context in which adolescents' behavior is occurring.

### 4.1 Overall neural reference space.

Our key analysis leveraged 21 fMRI studies and revealed that the neural reference space of adolescent decision-making encompassed regions largely consistent with neurobiological models of both adolescent risk-taking and social cognition, including the VS, IFG/insula and dmPFC.

Across human (Delgado, 2007; Galvan, 2010; Telzer, 2016) and animal (Berridge & Kringelbach, 2008) models, the VS has been recognized as a key node in reward/saliency processing and incentive-driven behaviors. As such, the VS plays a prominent role in neurobiological models of adolescent risk-taking behaviors, and it is proposed that risky decisions in the peer context may be even more rewarding during adolescence, as evidenced by increased VS activity when peers are present during adolescent risk-taking (Chein et al., 2011). The VS serves an adaptive role in positive contexts as well, for example in prosocial decision-making, where activity in the VS is interpreted as part of the "warm glow" of giving (Moll et al., 2006). The current findings confirm the prominent role of the VS in adolescent decision-making in social contexts.

The IFG was also part of the neural reference space. The IFG is related to a wide range of functions, including cognitive control (Aron & Poldrack, 2006; Cascio et al., 2015). Recent work has also associated the left vlPFC (i.e., IFG) with tendencies toward impulsive sensation seeking (Chase et al., 2017), as well as the moderation between behavioral responses to one's best friend's positive affect and risky behavior (Ambrosia et al., 2018). In the context of social cognition, the IFG has been implicated in (re)appraisal of social stimuli, emotional judgment, and top-down aspects of emotion recognition such as deciding what action to take based on someone's emotion (Blakemore, 2008; Nelson & Guyer, 2011; Guyer et al., 2012). In the emotion literature, the IFG is routinely involved in emotional experiences and perceptions, perhaps because it is allowing a person to draw on semantic emotion category knowledge to make meaning of their and others' affective feelings (Brooks et al., 2017; Lindquist et al., 2012). These more social-emotional functions of the IFG may explain its contribution to adolescent decision-making in social contexts, over the contribution of the dlPFC, for instance, which is more often linked to domain-general cognitive control (MacDonald, Cohen, Stenger, & Carter, 2000; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). Indeed, the IFG cluster we observed spanned both the IFG and anterior insula; it may thus be part of what has been termed the "frontoinsula," a cluster of brain regions that frequently co-activate as part of an extended brain network that responds to affectively salient stimuli (Seeley et al., 2007; Kleckner et al., 2017; Touroutoglou et al., 2012).

The anterior insula is also part of the so-called "salience network" (Seeley, et al. 2007) insofar as it represents affective states and helps guide attention during goal-directed behavior (Menon & Uddin, 2010). Our other work suggests that it more generally responds to pleasant and unpleasant stimuli (Lindquist et al., 2016) and represents the importance of social stimuli for humans (Aztil et al., in prep). These findings are consistent with the idea that the salience network is part of a broader group of brain regions (including those traditionally part of the so-called 'default mode network') that are involved in representing affective states and maintaining homeostasis of the organism (Kleckner et al. 2017). As a

highly social species, social others are certainly important to homeostasis for humans. In keeping with these findings, in social-affective contexts, the insula is associated with learning after social feedback (Jones et al., 2014) and the evaluation of others' mental states and emotional expressions (Blakemore, 2008; Lamm & Singer, 2010). Moreover, adolescents with high familial conflict show disrupted connectivity within aspects of this network (insula-VS connectivity) during risk-taking in the presence of their mother (Guassi Moreira & Telzer, 2018c). Although the insula remains largely overlooked in current neurobiological models of adolescent decision-making, the results of our meta-analysis underscore the key role of the insula in adolescent decision-making in a social context (cf. Smith et al., 2014).

Finally, our neural reference space included the dmPFC extending into the mPFC, a region included in the social brain model (Blakemore, 2008; Blakemore & Mills, 2014). The mPFC is often discussed as a region implicated in understanding others' mental states, with the dorsal peak found in our study generally attributed to mentalizing, or thinking about oneself and others' psychological states (Nelson et al., 2005; Blakemore, 2008; Blakemore & Mills, 2014; Jenkins & Mitchell, 2011; Denny et al., 2012). Some current neurobiological models of adolescent decision-making do recognize a role of the mPFC, such as in the dual systems model, which includes the mPFC in the socioemotional system that increases motivation to pursue rewards (Shulman et al., 2016). The role of the dmPFC may also differ in part based on task demands (e.g., dmPFC is also associated with the cognitive component of risk, but this part is cytoarchitecturally closer to the dorsal ACC; Van Duijvenvoorde et al., 2015). Nonetheless, our findings represent a more dorsal part of the mPFC that is not often discussed in the literature. In sum, many of the regions highlighted as part of our neural reference space of adolescent decision-making in social contexts involve regions outside current neurobiological models of adolescent decision-making.

## 4.2 Modulation of the neural reference space of decision-making in social contexts

The second goal of this meta-analysis was to examine how the neural reference space of decision-making in social contexts was modulated by different types of social context. In other words, we further delineated neural activity that was relatively more likely to occur during social influence decisions (i.e., when one's decisions are affected by others) and social outcome decisions (i.e., when one's decisions affect others).

### 4.2.1 Social influence decisions.—Social influence tasks yielded a cluster of regions associated with social cognition (IPL, TPJ and pSTS), highlighting the role of social brain regions when adolescents' decisions are affected by others - either in their presence or with actual feedback. This effect was found using a more liberal threshold than our other findings; as such the interpretation of this finding should be seen as more exploratory. However, given both our *a priori* hypotheses and the nascence of the field we opted to include these more liberal results as they may guide future research. Interestingly, while the dmPFC was part of the overall neural reference space, the TPJ and pSTS seem to be more specific to social influence. The TPJ and pSTS have been implicated in predicting biological movements (Frith & Frith, 2007),in understanding other people's mental states (Saxe, 2006) and beliefs about stimuli (social or otherwise) more generally (Mitchell et al., 2005). In the

context of social influence, adolescents likely recruit these regions to evaluate social norms and the perspectives of others, which in turn affects their behavior (Shaw, 2003; Telzer et al., 2018). While many of the studies included in the social influence category used versions of risk-taking tasks, we surprisingly did not find VS activity for this contrast. This is an interesting finding, given that it is often thought that peers may make risk-taking a more rewarding experience, as evidenced by heightened activation in VS during risk-taking with peers compared to alone during adolescence (Chein et al., 2011). It is possible that decision-making under social influence recruits regions implicated in social processing more consistently than VS when considering a broader range of behaviors beyond just risk-taking, such as in this meta-analysis. Taken together, the current findings implicate that it is crucial to take a broad approach to studying the neural correlates of social influence, as different neural processes may be implicated depending on the task behaviors and context used (cf. Van Hoorn et al., 2016) and modeling of task data (see e.g., Sherman et al., 2017).

**4.2.2    Social outcome decisions.—**Social outcome decisions elicited activity in the VS, supporting the idea that decisions that affect the outcomes of others are motivationally salient and rewarding to adolescents (Moll et al., 2006; Telzer, 2016; Do, Guassi Moreira, & Telzer, 2018c). VS activity is often associated with positively valenced affect (e.g., Forbes & Dahl, 2005), and so it could be argued that this effect is confounded by a difference in the valence of the behaviors studied in social outcome versus social influence decisions. In other words, social outcome tasks might include positively valenced behaviors, such as prosocial decisions, whereas social influence might include negatively valenced behaviors, such as risk-taking. However, this is highly unlikely given that the social outcome category also encompassed gambling for others, and the social influence category included neutral or positively valenced behaviors such as prosocial behavior. Given that there was a range of behaviors studied within each category, a more parsimonious explanation is that the act of making decisions that affect others is itself motivationally salient and rewarding for adolescents.

**4.2.3    Social actor type.—**Finally, we investigated how the neural reference space was modulated by social relationships across decision-making tasks in a social context. Given that the social context is so salient in adolescence, it is important to disentangle whether the closeness of social actors (i.e., known versus unknown others) differentially affects neural processing involved in decision-making. The present findings showed that decision-making in a social context in which known others are involved elicited more VS activity than when unknown others are involved, highlighting the motivational relevance of known others for adolescents (Telzer, 2016). This finding is in line with previous behavioral evidence showing that adolescents tend to be more prosocial towards friends than strangers (Guroglu et al., 2014; Padilla-Walker, Carlo, & Memmott-Elison, 2017), and close friendships, as opposed to broader peer groups, are protective for adolescents' mental health (Narr et al., 2017). Hence, when researchers use unknown social actors in studies to create a more controlled experimental environment (i.e., one in which adolescents do not have pre-existing beliefs about social actors), they may be misrepresenting the extent of VS activity recruited in everyday life when adolescents interact with known social actors.

Social interactions with unknown others elicited more subgenual ACC/amygdala activity. These regions are part of the salience network, and show heightened responding to threat, negativity, and the unknown (Masten et al., 2011; Lindquist et al., 2016). The thoughts, feelings and behaviors of unknown others may be relatively uncertain and hence require more information gathering. Adolescents need to figure out whether unknown others constitute a (social) 'threat', which in turn can affect subsequent decision-making. Taken together, our results highlight differences in neural recruitment depending on the social relationship, such that known others consistently elicit VS activity, while subgenual ACC/ amygdala is consistently recruited for unknown others.

### 4.3 A constructionist model of adolescent decision-making

Together, our results suggest that models of adolescent decision-making would be well advised to consider the role of neural systems involved in affect, cognitive control, *and* social information processing. Our findings are consistent with a constructionist approach to the mind (Barrett, 2017; Lindquist, 2013), which hypothesizes that all mental states can be decomposed into more basic affective, semantic, sensory, and cognitive control elements; brain networks supporting these functions are thought to combine to create the myriad mental states (emotions, cognitions, perceptions) that humans experience on a daily basis (Lindquist & Barrett, 2012; Barrett & Satpute, 2013).

A constructionist approach to adolescent decision-making describes the current findings and offers novel predictions for future research. For instance, it suggests that adolescent behaviors can be described as the combination of more basic processes such as affective salience (whether a person or situation is especially meaningful to the observer), social information processing (understanding the feelings and thoughts of the social actors involved), and cognitive control (whether an adolescent tries to actively regulate or inhibit their behavior). Each of these psychological functions has been associated with specific canonical neural networks (Barrett & Satpute, 2013; Lindquist & Barrett, 2012; McCormick et al., 2018; Smith et al. 2009; Spunt & Lieberman, 2013). Our constructionist approach predicts that adolescent decision-making in a given context will be associated with the relative activity within and between these networks and will vary as a product of development (e.g., age, pubertal status) and the context (e.g., the presence or type of peers).

Although no research to date has explicitly tested the constructionist hypothesis that between-network connectivity predicts different decision-making outcomes, some existing research is consistent with this approach. For instance, studies find that greater connectivity within the salience network (e.g., between the VS and insula) predicts adolescent risky decision-making (Guassi Moreira & Telzer, 2018c). Other studies find that greater connectivity between the salience network and social information processing network (e.g., the VS and mPFC) predicts adolescent risky decision-making (Qu et al. 2015). VS-mPFC connectivity is uniquely heightened during adolescence when adolescents think they are being watched by a peer (Somerville et al., 2013) and VS-mPFC connectivity at rest shows regionally specific linear age-related changes from childhood to late adolescence (Fareri et al., 2015). VS-mPFC connectivity subsequently correlates with age-related increases in testosterone levels (Fareri et al., 2015) as well as reward sensitivity (Van Duijvenvoorde et

al., 2016), cognitive control, and substance use (Lee & Telzer, 2016). On the one hand, such connectivity may be specific to reward-related processes, insofar as mPFC is a dopaminoceptive region with dopaminergic projections from the substantia nigra/ventral tegmental area (see Telzer, 2016). On the other hand, especially task-related increases in functional connectivity between VS-mPFC and VS-insula may represent the integration of social signals with motivational and affective processes that govern goal-directed behavior (Somerville et al., 2013). In keeping with this constructionist interpretation, other research finds evidence for increased functional connectivity within regions associated with social information processing *and* between these regions and regions associated with affective sensitivity, motivation, and cognitive control when adolescents experience social evaluation (McCormick et al., 2018). A limitation of our meta-analytic procedure is that we could not address functional connectivity. However, future research should continue to examine the dynamic coupling of these interacting neural systems as well as networks involved in cognitive control across different social contexts and across development to gain a deeper understanding of how diverse neural systems work together to support adolescent behavior.

### 4.4 Limitations and future directions

Although the current findings are central to the developmental period of adolescence, it is important to acknowledge that they may or may not be *unique* to adolescence. To date, the emerging neuroimaging literature on this topic is relatively small (i.e., we could only include 21 papers), which prevents the comparison of the adolescent neural reference space versus the neural reference space in other developmental periods. Moreover, the MKDA does not examine longitudinal changes, and so such studies were excluded in the present meta-analysis, precluding our ability to examine developmental trajectories. To further unpack the developmental trajectory of adolescent decision-making in social contexts, future studies should aim to include diverse age groups, especially children (ages <12; also see Li, 2017), as well as 'older' adult groups (age 30+instead of college students) as these are highly underrepresented in current developmental comparisons. As the developmental neuroimaging field is moving from cross-sectional studies to longitudinal designs, that allow within- and between-subject comparisons, this shift will ultimately provide a more comprehensive understanding of how individual differences and environmental processes impact developmental trajectories (Crone & Elzinga, 2015). Nevertheless, the current meta-analysis was the first empirical test of the neural reference space supporting adolescent decision-making in social contexts and can be considered a stepping stone for future research into this important topic.

In conclusion, we underscore the importance of integrating social contexts when studying adolescent neurocognition, and we provide meta-analytic evidence that dmPFC, VS and insula/IFG are consistently activated during adolescent decision-making in social contexts. In addition, we show that the neural reference space is modulated by the type of task (i.e., social influence or social outcome decisions) and the social actor (i.e., known vs unknown social actors). Our findings highlight the need for the field to broaden the lens and study brain regions associated with social information processing to gain traction on the processes supporting adolescent neurocognition in social contexts. While our results do not imply that social brain regions are implicated in a standard 'cold' decision-making task, such tasks may

not be truly representative of decision-making in real-life, which seldom takes place in a social vacuum. Exploration of broader brain networks implicated in adolescent decision-making in social contexts may lead to a refinement rather than verification of current neurobiological models (Pfeifer & Allen, 2016). These meta-analytic findings represent a first step towards refining current neurobiological models of adolescent decision-making. With further research, especially that increases our understanding of the dynamic interplay between networks supporting affective responding, cognitive control, and social information processing across development, the field can refine existing models to understand how the context shapes adolescent behavior. Ultimately, understanding the neural processes involved in adolescent decision-making will help us to solve the complex puzzle of why adolescents make adaptive decisions in some situations, but maladaptive decisions in other situations.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

## Acknowledgements

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## Highlights

- Social context plays an important role in adolescent decision-making

- Neurobiological models do not discuss brain regions implicated in social processing

- Meta-analysis tested neural coding for adolescent decision-making in social context

- dmPFC, IFG/insula and ventral striatum are consistently involved in this process

- Neurobiological models should incorporate social information processing regions
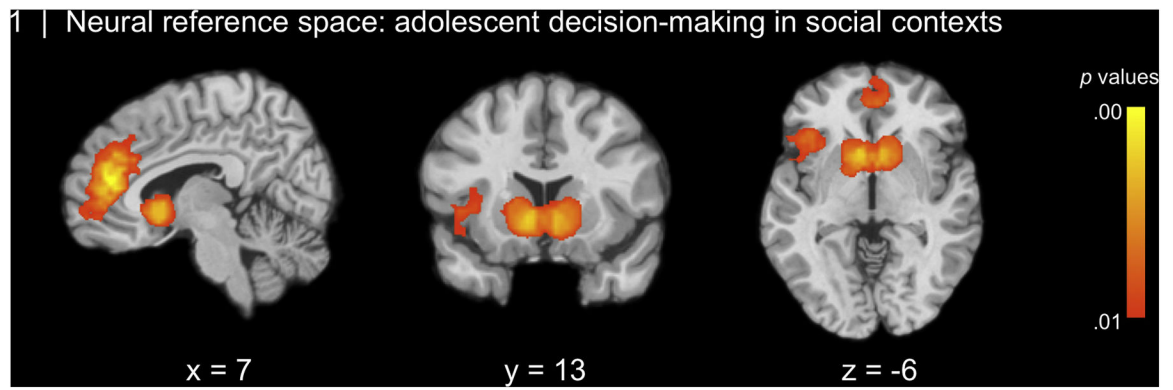
**Figure 1.**
During adolescence, decision-making in social contexts elicits activation in brain regions implicated in social processing (dmPFC), affective sensitivity (insula, ventral striatum), and cognitive control (IFG).
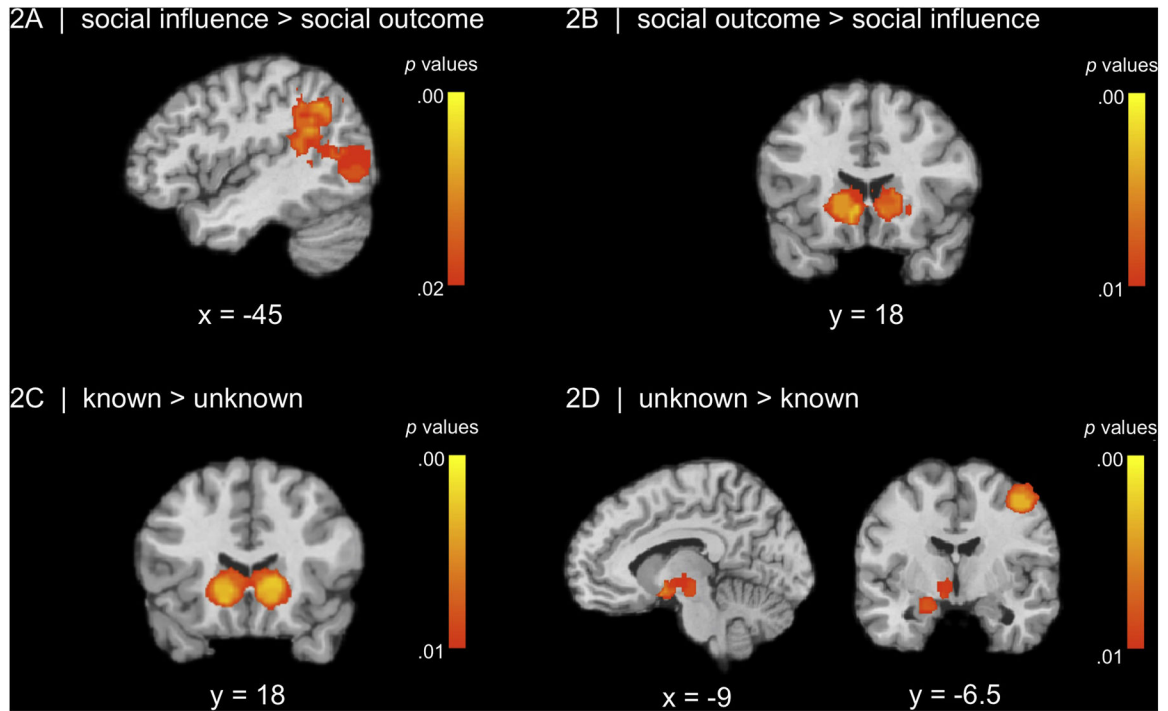
**Figure 2.**
(A) Social influence decisions > Social outcome decisions and other social tasks elicits activity in regions implicated in social processing (IPL, TPJ, pSTS), highlighting the contribution of the social brain, although at a slightly less stringent threshold of $p < .02$ (B) Social outcome decisions > Social influence decisions and other social tasks yields activation in the VS. (C) Decision-making with known > unknown others yields activity in the VS (D) Decision-making with unknown vs known others yields activation in the subgenual ACC/amygdala.

**Table 1.**

Overview of studies included in the meta-analysis (N = 21 studies, *N* = 1292 total participants), task description, and social context category. For an overview of excluded studies (*N* = 13 studies), see Supplementary Table 1.

| First author, year | Task | Description | Contrasts included | N (#F) | Age Range (Mean) | Social Context Category | Social Actor (specific person) |
|---|---|---|---|---|---|---|---|
| Braams & Crone, 2016 | Heads or tails gambling game | Participants guessed heads or tails and won or lost money depending on whether the computer picked the chosen side. Outcomes affected best friend or self.[1] | outcome friend > outcome self; outcome self > outcome friend | 249 (132) | 8.01–25.95 (14.5) | social outcome | Known (best friend) |
| Braams, 2017 | Heads or tails gambling game | Participants guessed heads or tails and won or lost money depending on whether the computer picked the chosen side. Outcomes affected best friend, self, or mother.[2] | win for friend > lose for friend; win for mom > lose for mom | 233 (117) | 9.9–26.6 (16.1) | social outcome | Known (best friend, parent) |
| Chein, 2011 | Stoplight Task | Computerized driving game in which participants chose to stop (safe decision) or go (risky decision) at yellow lights of intersections. Goal is to reach the end of the track as fast as possible. Played alone and with peers observing.[3] | adult decisions > adolescent decisions | 40 (21) | 14–18, 19–22, 24–29 (15.7, 20.6, 25.6) | social influence | Known (same-sex same-age friends) |
| Guassi Moreira, 2018a | Stoplight Task | Computerized driving game in which participants chose to stop (safe decision) or go (risky decision) at yellow lights of intersections. Goal is to reach the end of the track as fast as possible. Played with | safe decision mother > safe decision adult; risky decision mother > risky decision adult | 23 (9) | 15 (15.22) | social influence | Known (Parent) Unknown (adult "expert in adolescent driving behavior") |

| First author, year | Task | Description | Contrasts included | N (#F) | Age Range (Mean) | Social Context Category | Social Actor (specific person) |
|---|---|---|---|---|---|---|---|
| | | a parent and an unknown adult observing. | | | | | |
| Gunther Moor, 2012 | Dictator game (DG) | Played Cyberball before DG to establish social exclusion and inclusion. In DG participants divided coins between themselves and other players (team 1: includers; team 2: excluders). | DG excluders > DG includers; DG excluders > DG includers in 19–21 group vs younger age groups | 53 (31) | 10–12, 14–16, 19–21 (11.8, 15.74, 20.38) | social outcome | Unknown (team 1: includers; team 2: excluders) |
| Guroglu, 2011 | Ultimatum Game (UG) | UG in which participants were responders that accepted or rejected offers from the proposer. | accept > reject; unfair > fair w/fair alternative; unfair > fair w/ hyperfair alternative | 68 (32) | 10.3–20.4 10, 13, 15, 20 (10.4, 13.4, 15.4, 20.4) | social outcome | Unknown (avatars) |
| Op de Macks, 2016 | Jackpot Task | Participants played a gambling task in which they decided to play or pass, with variable risk levels (33% or 67% chance to win) and stakes (1 or 3 points), and received either social rank feedback or monetary feedback. | social play > monetary play | 58 (58) | 11–13 (12.4) | social influence | Unknown (same-sex same-age peers) |
| Peake, 2013 | Stoplight Task; Cyberball | Computerized driving game in which participants chose to stop (safe decision) or go (risky decision) at yellow lights of intersections. Goal is to reach the end of the track as fast as possible. Participants played Stoplight, were excluded in Cyberball, then played Stoplight again, with the excluders watching the participant. | stop decision post exclusion > stop decision pre exclusion; go decision pre exclusion > go decision post exclusion; stop decision pre exclusion > stop decision post exclusion | 20 (10) | 14–16.8 (15.3) | social influence | Unknown (peers) |

| First author, year | Task | Description | Contrasts included | N (#F) | Age Range (Mean) | Social Context Category | Social Actor (specific person) |
|---|---|---|---|---|---|---|---|
| Perino, 2016 | Social Go-NoGo Task | Participants completed a social go-nogo task with the target stimuli (letters) superimposed on socially appetitive and socially aversive scenes. Participants had to withhold button presses on trials with an X letter. | socially appetitive > socially aversive | 35 (20) | 12–17 | other - social distraction | Unknown (pictures of social scenes) |
| Rodrigo, 2014 | Social Context Decision Task | Participants read short passages describing social situations in which they were accompanied by a close friend and had to decide between a dangerous or a safe choice (risk condition) or between 2 neutral choices (ambiguous condition). | risky decision > ambiguous decision; risky > ambiguous adolescent vs adult; dangerous > safe; dangerous > safe young adult vs adolescent | 60 (30) | 17–18, 21–22 (17.5, 21.4) | other - scenarios with peers | Known (close friend) |
| Sherman, 2016 | Instagram Task | Participants were shown a feed of Instagram photos from peers and themselves (some risky, some neutral) with the number of likes displayed (popular or unpopular), and could decide to like photos or move on to the next photo. | neutral image unpopular > neutral image popular; risky image unpopular > risky image popular; own image unpopular > own image popular; risky image > neutral image; risky image < neutral image; own neutral image > other neutral image [4]; own risky image > other risky image [8] | 32 (18) | 13–18 | social influence | Unknown (peers) |
| Steinmann, 2014 | Ultimatum Game | Participants were responders and accepted or rejected offers from the proposer. | unfair - fair decision for adult > unfair - fair decisions for children; unfair - fair decision for adult < unfair – fair decisions for children; unfair - fair decision for adolescents > unfair – fair decisions for children | 45 (20) | 8–12, 13–18, 19–28 (10.2, 15.5, 24.8) | social outcome | Unknown |

| First author, year | Task | Description | Contrasts included | N (#F) | Age Range (Mean) | Social Context Category | Social Actor (specific person) |
|---|---|---|---|---|---|---|---|
| Telzer, 2011 | Family Assistance task | Participants accepted or rejected monetary offers that would benefit their families or themselves. Choices were either costly or non-costly donations or costly or non-costly rewards. | Accept costly donation > Accept a non-costly reward | 25 (13) | 19–20 (20.2) | social outcome | Known (family) |
| Telzer, 2013 | Family Assistance task | Participants accepted or rejected monetary offers that would benefit their families or themselves. Choices were either costly or non-costly donations or costly or non-costly rewards. | Accept costly donation > control; Accept non-costly donation > control; Accept costly donation > Accept non-costly donation; Accept non-costly donation > Accept costly donation | 32 (18) | 15–17 (16.3) | social outcome | Known (family) |
| Telzer, 2015 | Stoplight Task | Computerized driving game in which participants chose to stop (safe decision) or go (risky decision) at yellow lights of intersections. Goal is to reach the end of the track as fast as possible. Participants completed the task alone and with their mother watching. | Risky decision (collapsed over mom and alone context); Stop decision > Go decision (collapsed over mom and alone context); Go decision > stop decision (collapsed over mom and alone context); Pass decisions (collapsed over mom and alone context); Stop decision w/ mom > Stop decision alone; Stop decision w/ mom > control; Go decision w/mom > go decision alone | 25 (10) | 14 (14.43) | social influence | Known (mother) |
| Telzer, 2017 [*] | Cyberball; Stoplight Task | Played Cyberball and were excluded by 2 unknown peers; Then completed a computerized driving game in which participants chose to stop (safe decision) or go (risky decision) at yellow lights of intersections. Goal is to reach the end of the track as fast as possible in order to | Risky decision CV > Risky decision NV; Risky decision NV > Risky decision CV; Safe decision CV > safe decision NV | 46 (46) | 14.8–16.1 (15.3) | social influence | Unknown (peers) |

| First author, year | Task | Description | Contrasts included | N (#F) | Age Range (Mean) | Social Context Category | Social Actor (specific person) |
|---|---|---|---|---|---|---|---|
| | | earn points for their team. Compared a chronically victimized (CV) group with a non-victimized group (NV). | | | | | |
| van den Bos, 2011 | Trust Game | Participant acts as Player 2, the trustee, in the Trust Game. When Player 1 gives money to Player 2, participant can choose to share increased amount of money with Player 1 or keep the given money. | Receiving trust > No trust (all ages); Receiving trust > no trust receiving[5]; Choose to defect > choose to reciprocate (all ages); Choose to reciprocate > choose to defect (all ages); Choose to defect > choose to reciprocate[6] | 54 (30) | 12–22 (16.2) | social outcome | Unknown (peers) |
| van den Bos, 2014 * | mini- Ultimatum Game | Participants decide whether they accept or reject a monetary offer from another player. Offers were either fair, unfair, no alternative, and hyperfair alternative. | Accept unfair offer > Reject unfair offer (entire sample) | 34 (0) | 15.0–22.0 (17.71) | social outcome | Unknown (peers) |
| van Hoorn, 2016 | Public Goods Game | Participant could donate tokens to the group or keep for themselves in one of three conditions: peers observing, peers giving feedback, or no peers present (i.e., alone). | Prosocial decision w/ someone watching > prosocial decision when alone; Prosocial decision w/ feedback > prosocial decision when alone | 61 (32) | 12–13, 15–16 (12.93, 16.08) | social influence | Unknown (peer actors) |
| Verdejo-Garcia, 2015 | Ultimatum Game | Participants decide whether they accept or reject a monetary offer from another player. Examining group differences between adolescents in excess weight (EW) vs. normal weight (NW) | unfair decision NW > fair decision NW; unfair decision > fair decision[7]; reject offer NW > accept offer NW; reject offer > accept offer[8] | 80 (49) | 12–18 (Normal weight: 15.32, Excess weight: 15.06) | social outcome | Unknown (peers) |
| Welborn, 2015 | Artwork Ratings | Participants rated artwork before the scan session and during the scan were shown actual ratings | Peer influence > no influence; No influence > peer influence; Parental influence > no influence; Parent and | 19 (7) | 16.44–18.43 (17.56) | social influence | Known (peers from same school; parents) |

| First author, year | Task | Description | Contrasts included | N (#F) | Age Range (Mean) | Social Context Category | Social Actor (specific person) |
|---|---|---|---|---|---|---|---|
| | | made by their parents and peers of the same pieces of art. Participants then made their ratings again to examine changes due to parental or peer influence. | peer influence > no influence | | | | |

*Notes.* Social context was coded into 3 categories: social outcome decisions, social influence decisions, and other. Social actor was coded as known or unknown.

[1] Analyses focused on processing outcomes, but there was no jitter between events, so included in meta-analysis to retain power. Only timepoint 1 whole brain analyses included.

[2] Only whole brain analyses included.

[3] Interactions age group x social context could not be included.

[4] ROI analysis.

[5] Trust versus no trust, comparing 2 youngest with oldest age group.

[6] Choice to defect > reciprocate, comparing youngest age group to two older age groups.

[7] Unfair offer > fair offer comparing normal weight *vs* excess weight.

[8] Reject offer < accept offer comparing normal weight *vs* excess weight.

[*] All studies were conducted with non-patient populations. 'Special' populations included in this meta-analysis were: Telzer 2017 Chronically victimized and non-victimized females; Van den Bos 2014 Antisocial teens (some of which had a diagnosis) and healthy controls (age and IQ matched); Verdejo Garcia 2014 normal weight and excess weight (high BMI).

**Table 2.**

Coordinates for overall neural reference space, thresholded voxel-wise at $p < .01$, cluster-wise FWE-corrected $p < .05$.

| Region | k | x | y | z | max | mean |
|---|---|---|---|---|---|---|
| *Neural reference space all studies* | | | | | | |
| R Dorsomedial Prefrontal Cortex (dmPFC) | 631 | 6 | 42 | 15 | 0.23 | 0.12 |
| R Dorsal Anterior Cingulate Cortex (dACC) | *a* | 3 | 27 | 27 | 0.15 | 0.10 |
| L Medial Prefrontal Cortex (mPFC) | *a* | −3 | 45 | 0 | 0.14 | 0.10 |
| R Ventromedial Prefrontal Cortex (vmPFC) | *a* | 9 | 51 | −9 | 0.11 | 0.09 |
| L Ventral Striatum (VS) | 470 | −6 | 12 | −6 | 0.18 | 0.12 |
| R Ventral Striatum | *b* | 9 | 9 | −9 | 0.17 | 0.12 |
| L Insula | 299 | −39 | 18 | 0 | 0.14 | 0.10 |
| L Inferior Frontal Gyrus (IFG) | *c* | −36 | 27 | −9 | 0.14 | 0.10 |

*Abbreviations.* k = cluster size in mm$^3$; x, y, z = coordinates in Montreal Neurological Institute (MNI) space; max = maximum value within cluster; mean = average value within cluster. L = left, R = right

[a] dmPFC cluster

[b] = ventral striatum cluster

[c] insula/IFG cluster.

**Table 3.**

Coordinates for meta-analytic contrasts, thresholded voxel-wise at $p < .01$, except where noted by $*p < .02$, cluster-wise FWE-corrected $p < .05$.

| Region | k | x | y | z | max | mean |
|---|---|---|---|---|---|---|
| *Contrast: social influence decisions > social outcome decisions and other tasks** | | | | | | |
| L Inferior Parietal Lobule (IPL) | 615 | −45 | −57 | 39 | 0.19 | 0.10 |
| L Superior Temporal Gyrus (STS) | d | −42 | −51 | 24 | 0.17 | 0.12 |
| L Supramarginal Gyrus (TPJ) | d | −45 | −45 | 39 | 0.15 | 0.10 |
| L Angular Gyrus (TPJ) | d | −48 | −69 | 42 | 0.14 | 0.10 |
| L Middle Temporal Gyrus | d | −42 | −63 | 12 | 0.12 | 0.10 |
| L Middle Occipital Gyrus | d | 0.36 | 0.72 | 9 | 0.08 | 0.08 |
| | | | | | | |
| *Contrast: social outcome decisions > social influence decisions and other tasks* | | | | | | |
| L Ventral Striatum (VS) | 365 | −6 | 18 | −3 | 0.24 | 0.15 |
| R Ventral Striatum (VS) | e | 9 | 18 | −6 | 0.21 | 0.15 |
| L Putamen | e | −24 | 15 | 9 | 0.15 | 0.13 |
| R Putamen | e | 24 | 21 | −3 | 0.12 | 0.12 |
| | | | | | | |
| *Contrast: social actors known > unknown* | | | | | | |
| R Ventral Striatum (VS) | 445 | 18 | 18 | 3 | 0.36 | 0.25 |
| L Ventral Striatum | f | −9 | 18 | 0 | 0.36 | 0.25 |
| | | | | | | |
| *Contrast: social actors unknown > known* | | | | | | |
| R Subgenual Anterior Cingulate (sgACC) | 330 | 3 | 18 | −12 | 0.1 | 0.10 |
| L Amygdala | g | −21 | −9 | −18 | 0.14 | 0.11 |
| L Thalamus | g | −6 | −21 | −3 | 0.11 | 0.09 |
| R Lentiform Nucleus | g | 18 | 0 | −6 | 0.1 | 0.09 |

| Region | k | x | y | z | max | mean |
|---|---|---|---|---|---|---|
| R Ventral Striatum (VS) | g | 3 | 3 | −3 | 0.2 | 0.11 |
| R Postcentral Gyrus | 291 | 51 | −12 | 51 | 0.19 | 0.13 |

*Abbreviations.* k = cluster size in mm³; x, y, z = coordinates in Montreal Neurological Institute (MNI) space; max = maximum value within cluster; mean = average value within cluster.

[d] IPL/TPJ/pSTS cluster

[e] ventral striatum cluster

[f] ventral striatum cluster

[g] subgenual ACC/amygdala cluster.