Learning whom not to trust across early adolescence: a longitudinal neuroimaging study to
trusting behavior involving an uncooperative other

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Abstract

Early adolescence may be an important period for developing sensitivity to uncooperative behavior. With this functional magnetic resonance imaging study, we examined longitudinal changes in trusting behavior and their neural correlates in regions of interest (ROIs) selected *a priori*: the medial prefrontal cortex (mPFC), dorsal anterior cingulate cortex (dACC), left anterior insula (AI), bilateral ventral striatum, and right dorsal striatum. Participants played the investor in a Trust Game with an uncooperative trustee (an anthropomorphic cartoon) three times, with one year between each wave. We preregistered our hypotheses and analytic plan. In total, 160 scan sessions of 77 participants (age at wave 1: $M=13.89$) were included in the analyses. First, we examined changes in trusting behavior involving an uncooperative other, and showed that participants' investments decreased with wave. Next, we examined whether the investment and repayment phase yielded enhanced activity in the ROIs. In each phase we observed increased activity in the mPFC, dACC, and dorsal striatum, but no effects were found in the bilateral ventral striatum (and AI did not reach significance after multiple comparisons correction). Finally, we examined whether ROI activity changed with wave. During the repayment phase, dorsal striatum activity increased with wave (although this finding did not survive Bonferroni correction, it closely approached our threshold for significance). Together, these results indicate that young adolescents become increasingly responsive to uncooperative behavior; that trust behavior robustly enhanced activity in brain regions previously related to trust and decision-making in social context; and increased involvement of dorsal striatum across early adolescence.

Keywords: Adolescence, trust game, cooperation, fMRI, development

1. Introduction

Relative to children, adolescents spend more time with peers (Nelson et al., 2016). As young adolescents enter this more complex social world, social decision-making skills become essential for adhering prevailing social group norms and establishing ties with peers. One type of complex social decisions encompasses the dilemma of whether to show trust in peers. Trust is often expressed in the form of a favor or sharing resources, which creates the possibility of a mutual benefit (Cox, 2004; Gunnthorsdottir et al., 2002). As such, decisions to trust another person are related to prior beliefs about how the other will respond. When trust is reciprocated, showing trust may contribute to cooperative social interactions and over time to a positive social bond (Fareri, 2019). However, reciprocation is not guaranteed and trusting behavior may turn out to be a costly decision (Fett et al., 2014b). Therefore, to protect oneself from wasting resources, it is important to learn in early adolescence whom not to trust and, most importantly, to adjust behavior accordingly. With this three-wave annual study, we aimed to obtain a thorough understanding of adolescents' ability to adapt their behavior to uncooperative others across early adolescence from a neuroscience perspective.

1.1. Trust game

Social decisions about whether to trust someone are often examined using an economic exchange paradigm called the 'Trust Game' (sometimes called the "Investment Game") (Berg et al., 1995). First, in the investment phase of this game, the first player (investor) receives an endowment of which nothing or any portion can be invested in another player (trustee). If the investor expresses trust in the trustee by sending money, the invested amount is tripled and sent to the trustee. Second, in the repayment phase, the trustee decides to pass nothing or any portion of the (tripled) amount back to the investor.

Traditionally, it is argued that trust is violated if the trustee returns an amount no greater than the investor's original investment (Berg et al., 1995).

For the investor, the decision of whether to trust an unfamiliar player in the first (or – so far – only) encounter might be especially difficult to take, because of the lack of information about the other's willingness to reciprocate. A long history of research shows that the majority of the investors — of varying ages — trust the other player with a portion of their endowment (Johnson & Mislin, 2011; Sanfey, 2007; Sutter & Kocher, 2007). This expression of trust may be motivated by the expectation of a positive repayment and/or concern for the other player (Bellucci et al., 2017; Camerer, 2003). Tentatively, for the investor, a violation of trust may be unexpected and require a shift to a more uncooperative mindset and uncooperative behavior. This makes *repeated* interactions with unfamiliar *uncooperative* trustees of special interest.

1.2. Trusting decisions across adolescence

Cross-sectional studies have shown that adolescents' ability to incorporate the interaction partner's cooperativeness into trusting decisions during repeated interactions improves as they grow older. For example, in terms of investments, middle and older adolescents (16 and 21 years of age) distinguished more between cooperative, uncooperative, and neutral interaction partners than young adolescents (10 years of age) (van den Bos et al., 2012). In line with these findings, older participants trusted cooperative interaction partners to a greater extent than younger participants (sample age range 14-49 years) (Fett et al., 2014a), although in other samples (age range 13-18 and 16-27 years), no age-related changes in trusting behavior involving cooperative or uncooperative partners were reported (Fett et al., 2014b; Lemmers-Jansen et al., 2017). Middle and older adolescents (14-15 and 16-18 years of age, respectively) have been found to be better at overcoming a bias toward a neutral interaction partner presented as "good" than young

adolescents (12-13 years of age), by more quickly adjusting their investment behavior to the “real” character of the interaction partner (Lee et al., 2016). In contrast, no differences in changes in trusting behavior to neutral partners presented as “bad” were found between age groups (Lee et al., 2016). Taken together, these cross-sectional findings suggest that, with age, adolescents become increasingly sensitive to their interaction partner’s willingness to cooperate when engaging in repeated interactions.

Interestingly, Fett et al. (2014b) demonstrated that adolescents’ ability to take others’ perspectives contributed to the decision-making process of trusting others. More specifically, adolescents (13-18 years of age) more proficient with taking others’ perspective overall trusted unfamiliar others more than those less proficient. Intriguingly, proficient perspective-takers were also quicker to decrease their investments in exchanges with an uncooperative other. As such, perspective-taking abilities may contribute to the formation of a mental representation of others in interactions involving trust (Fett, Shergill, et al., 2014), which may become especially useful when interacting with uncooperative other. These findings highlight early to middle adolescence as a developmental window for the social cognitive skills key to adjusting social behavior to uncooperative others.

1.3. Neural mechanisms underlying trust

Trust, or the intention to cooperate, reflects the complex nature of social relationships as it taps into several underlying social cognitive processes (King-Casas et al., 2005). Given that trust reciprocation is not guaranteed, keeping track of social stimuli that affect decisions whether to trust an individual is key in social interactions. Important social cognitive processes in social interactions are perspective-taking abilities (Fett et al., 2014b), to evaluate whether one’s decisions result in the desired outcome, and to monitor one’s behavior (Krueger & Meyer-Lindenberg, 2019). With the current study, we aimed to examine neural correlates proposed to relate to these social cognitive processes to obtain a better

understanding of decision-making involving trust and processing the subsequent repayment in young adolescents over time.

1.3.1. *Ventral and dorsal striatum*

A meta-analysis (based on predominantly adult samples) on the neural mechanisms underlying behavior in the Trust Game shows that trusting decisions in the investment phase robustly involve the nucleus accumbens, part of the ventral striatum, when making decisions during repeated interactions (Bellucci et al., 2017). Furthermore, the caudate nucleus, part of the dorsal striatum, was shown to be involved in processing feedback of the interaction partner in the repayment phase. As such, the ventral striatum is hypothesized to be involved in anticipating the outcome of the interaction, whereas the dorsal striatum might be involved in feedback learning (Bellucci et al., 2017). In other words, the ventral and dorsal striatum are likely to be involved in reward-learning processes crucial for learning whom to trust (Krueger & Meyer-Lindenberg, 2019).

Because of the striatum's key role in trusting behavior in predominantly adult samples (Bellucci et al., 2017), age-related changes of striatum involvement in trusting behavior have been investigated. For instance, Fett et al. (2014a) found that when investing in a cooperative interaction partner, dorsal striatum activity declined with age (age range 13-49 years). Furthermore, whereas no age-related changes in striatum activity were found during the investment phase in another sample consisting of middle adolescents, older adolescents, and young adults (16-27 years of age), dorsal striatum activity increased with age when receiving the returned amount from both cooperative and uncooperative interaction partners (Lemmers-Jansen et al., 2017). Finally, with another study from this research group, Lemmers-Jansen et al. (2019) observed differential age-related changes (range 13-19 years) in dorsal striatum activity in males and females when making trusting decisions during the investment phase involving a cooperative partner. Overall, these

findings support the hypothesis that the dorsal striatum is involved in interactions involving trust across adolescence.

1.3.2. Neural sensitivity to the social context in adolescence

Whereas Bellucci et al. (2017) examined the neural mechanisms underlying trust in predominantly adult samples, to our knowledge there is no meta-analysis about neural mechanisms of trust in adolescents specifically. However, in a recent meta-analysis, van Hoorn et al. (2019) identified brain regions that adolescents robustly activate in contexts involving others (“social contexts”), which may by extension also play a role in trust interactions across adolescence. These brain regions included the medial prefrontal cortex (mPFC; also encompassing the dorsal anterior cingulate cortex [dACC]), the anterior insula (AI) extending toward the inferior frontal gyrus (IFG), and the ventral striatum.

The mPFC and dACC have been related to trust in prior developmental studies. Younger participants showed more activity in the mPFC and dACC than older participants in the investment phase during interactions with a cooperative partner (Fett et al., 2014a). It has been hypothesized that this reflects social learning processes related to monitoring outcomes of decisions and attributing traits to others (Krueger & Meyer-Lindenberg, 2019; Lee & Seo, 2016; van den Bos et al., 2011). Furthermore, the AI and IFG are proposed to respond to affectively salient contexts, such as social settings (Kohn et al., 2014; van Hoorn et al., 2019). Moreover, Bellucci et al. (2017) demonstrated robust involvement of the AI in trusting decisions in one-shot Trust Games. Finally, in line with Bellucci et al. (2017), van Hoorn et al. (2019) propose a key role for the ventral striatum in reward-processing in the social context. Taken together, these findings (van Hoorn et al., 2019) point to the mPFC, dACC, AI, and ventral striatum as brain regions potentially implicated in adolescents’ trust interactions.

1.4. The current study

Early adolescence may be an important period for developing sensitivity to uncooperative behavior (Fett et al., 2014b; Lee et al., 2016). With the current three-wave annual study, we aimed to extend existing cross-sectional work by examining longitudinal changes in repeated trust investments in unfamiliar uncooperative agents across early adolescence (12-15 years of age). Furthermore, we examined involvement of candidate brain regions implicated in trust (ventral and dorsal striatum, mPFC, dACC, and AI) during the investment and repayment phase and longitudinal changes across early adolescence (Bellucci et al., 2017; van Hoorn et al., 2019). To do so, across three waves separated by one year, participants played the Trust Game while functional magnetic resonance brain images were acquired. Participants played the role of the investor in a free-choice Trust Game and engaged in repeated interactions with an uncooperative trustee (whose uncooperative character was not communicated to the participants). The role of the uncooperative agent was fulfilled by a virtual anthropomorphic cartoon. This was done to avoid the need to deceive participants into thinking that they were interacting with another human being. With regards to behavioral responses in the Trust Game, we hypothesized that adolescents become increasingly sensitive to the uncooperative character of the interaction partner across early adolescence (Lee et al., 2016). As such, we expected that participants would (linearly) decrease their investment in the uncooperative agent as they grew older. With regards to the neural mechanisms underlying decisions in the investment and repayment phase, we expected enhanced ventral striatum activity in the investment phase and dorsal striatum activity in the repayment phase (Bellucci et al., 2017). However, since the role of the ventral and dorsal striatum in adolescents during the Trust Game remains elusive, we also explored ventral striatum involvement in the repayment phase and dorsal striatum involvement in the investment phase. Although we hypothesized involvement of dmPFC, dACC, and AI in the Trust Game, we did not have specific expectations about

involvement of these brain areas in particular phases. Therefore, we also explored dmPFC, dACC, and AI involvement in the investment and repayment phase. Finally, we explored linear as well as non-linear (quadratic) longitudinal changes in ventral striatum, dorsal striatum, dmPFC, dACC, and AI activity in the investment and repayment phase. We controlled for sex in all of our analyses based on prior studies reporting sex differences in trusting behavior (Lemmers-Jansen et al., 2017; van de Groep et al., 2020). We pre-registered our research questions, hypotheses, and analysis plan.

2. Methods

2.1 Preregistration and codes

We pre-registered our research questions, hypotheses, and analysis plan here: <https://osf.io/5nurp>. R codes are available here: <https://osf.io/b9mdh/>; codes to analyze the fMRI data here: https://github.com/marietvbuuren/trust_longitudinal. Data cannot be made publicly available due to privacy law regulations in The Netherlands, but data will be available upon request and can only be used in collaboration with one of the research team members.

2.2. Participants

The current functional magnetic resonance (fMRI) study is part of a larger research project called “#SOCONNeCT” (conducted at Vrije Universiteit Amsterdam; for details, see (van Buuren et al., 2021; van Buuren et al., 2020), and entailed three waves separated by one year. The first wave of data was collected in 2018. In the first wave of the study, there were 84 participants of which 36 females and 48 males ($M_{\text{age}} = 12.90$, $SD_{\text{age}} = 0.40$) (first wave data also reported in Sijtsma et al. (*submitted*)). All these participants were invited to participate in later waves. In the second wave, 60 participants participated (33 males and 27 females; $M_{\text{age}} = 13.89$, $SD_{\text{age}} = 0.42$; 16, 7, and 1 did not participate due to dental braces, a loss of interest or time, and anxiety for being in the scanner, respectively), and in the third wave 48 participants (26 males and 22 females; $M_{\text{age}} = 14.97$, $SD_{\text{age}} = 0.49$; 18 did not

participate due to dental braces, 15 due to loss of interest or time, 2 due to anxiety, and 1 due to unidentified reasons. In total, 46 participants participated in all three waves.

We excluded participants from all analyses based on a-priori defined criteria. Most of the excluded scan sessions (15, 6, and 6 at wave 1, 2, and 3, respectively) were excluded due to excessive motion (> 3 mm, one voxel size). Additionally, one participant scanned at wave 1 and 2 was excluded because of an incidental brain abnormality finding. In addition, we excluded 5 sessions (4 took place in wave 1, and 1 in wave 2) in which participants failed to respond within the required time frame of 3000 ms on more than 1/3 (i.e. 9) of the experimental trials within waves.

To summarize, data of 32 sessions (16.7%) were excluded from analyses (19, 7, and 6 sessions related to wave 1, 2, and 3, respectively). Of the final sample for analyses, participants' mean age was 12.90 ($SD = 0.45$, ranging from 11.61 to 14.22) of which 29 females and 36 males at wave 1; 13.89 ($SD = 0.44$, ranging from 12.62 to 15.20) of which 23 females and 30 males at wave 2; and 15.04 ($SD = 0.49$, ranging from 13.63 to 16.37) of which 19 females and 23 males at wave 3. In sum, we included 160 sessions (65, 53, and 42 of wave 1, 2, and 3, respectively) of 77 participants.

In the Supplementary Materials, we report an examination of whether the sample of participants who dropped out at wave 2 or 3 differed from the sample who continued participation in age, sex, investments, and investment and repayment phase ROI contrast estimates for experimental vs. control trials (also see Supplementary Figure 1). In short, results suggest no group differences except for the ROI estimates of the mPFC, dACC, and left AI obtained at wave 1. Results suggest that those ROI estimates are higher for participants who participated in wave 3 than for those who dropped out at wave 3. Therefore, results suggesting a longitudinal increase with wave in these particular ROI investment phase [experimental $>$ control] estimates should be interpreted with caution as the data points of wave 3 may be biased.

2.3. Procedure

This study was reviewed and approved by the institutional review board (VCWE, Faculty of Behavioral and Movement Sciences, VU Amsterdam, The Netherlands). Before the first scan session started, all participants and their parent(s)/caregiver(s) provided written consent for participation. Participants received instructions for the Trust Game, which comprised experimental and control trials (see section 2.4). Additionally, participants were familiarized with the fMRI scanner environment with a mock scanner. In the mock scanner, they played a practice version. In the experimental practice trials, participants played the role of the investor. To prevent learning effects, the repayment always matched the investment. In addition, the role of the trustee was not played by the social agent introduced in the fMRI task (explained below). Rather, they played this game by themselves.

2.4. Trust Game

Participants played the Trust Game while functional brain images were acquired (Berg et al., 1995). The Trust Game entailed 27 experimental and 27 control trials (see Figure 1). These trials were presented in three blocks (with an 18 second break) in pseudorandom order ensuring that no more than three trials from the experimental or control condition appeared in a row (Sijtsma et al., *submitted*).

2.4.1. Experimental trials

Participant played the role of the investor in a free-choice repeated Trust Game. The role of the Trustee was fulfilled by a social partner called “Corti”, an anthropomorphic animated brain. Participants did not receive any information about Corti’s cooperativeness. Experimental trials started with a cue screen (1000 ms) showing that they were asked to make an investment between 0 and 10. Then, the investment phase started with participants deciding about the amount of their investment (3000 ms). During this procedure, the cursor was set to 5 by default. Participants used their right index finger to move the cursor to the

left to lower values and the right middle finger to the right to higher values. To select their choice of investment, they pressed a button with their left index finger, after which the screen turned green. Next, participants' investment was shown in a bar indicating the proportion of their investment relative to the maximum amount for 1000 ms, which ended the investment phase.

Before sending the investment to interaction partner Corti, the amount was tripled. Next, a screen was shown (1000-5000 ms, mean duration of 3000 ms; "waiting" screen) during which the partner decided what to do with the investment, which was followed by a fixation cross (500 ms). The repayment phase started with an outcome screen (3000 ms) displaying how much Corti returned to the participant and kept. The proportion of the repayment and kept amount was presented in bars. The repayment phase ended with a screen (2500 ms) displaying the resulting distribution (in bars) of money between the participant and the partner of that trial. The experimental trial ended with a fixation cross (1500-5500 ms, mean interval 3500).

To ensure uncooperative behavior by the interaction partner, partner responses were modeled by an algorithm. For the repayment, the investment made by the participant was multiplied by a factor of 0.50, 0.75, or 1.00 and rounded to 50 cents. As such, trusting the partner never paid off as the maximum repayment was the same amount as the investment, and the minimum repayment half of the investment. At the start of the game, the multiplying factor used for the first repayment occurred with equal probability of 0.33. For subsequent trials, the multiplying factor was determined by the participant's behavior.

Probabilities of multiplying factors 1.00, 0.75, or 0.50 occurring remained stable when participants decreased or did not change their current investment compared with their previous investment. However, when participants increased their investment, the probability for a smaller multiplying factor for repayment occurring also increased. In other words, a smaller proportion of the investment was more likely to be repaid, which led the interaction

partner to become more uncooperative. In more technical terms, from the probability of 0.33 of one of three multiplying factors occurring, the probability of multiplying factor 1.00 occurring *decreased* with 0.05 and of multiplying factor 0.75 and 0.50 occurring *increased* with 0.025. After seven investment increases, probabilities of multiplying factor 1.00, 0.75, or 0.25 occurring dropped to 0.00 and rose to 0.50 and 0.50, respectively, after which they remained stable across the remaining trials.

2.4.1.1. Investments. To obtain a measure of the amount invested as a proxy of trust, trials in which participants did not make an investment in time were omitted from analyses. Overall, at wave 1, 62 participants failed to respond in time to 4.29 experimental trials on average ($SD = 5.53$, range 1-27); at wave 2, 32 participants failed to respond in time to 2.34 experimental trials on average ($SD = 2.21$, range of 1-12); at wave 3, 16 participants failed to respond to 2.13 experimental trials ($SD = 1.71$, range of 1-7). To obtain a measure of *mean* investment, participants' investments across trials were averaged within waves. We also inspected extreme mean investment outliers (> 3 SDs deviation from the mean) within waves, and winsorized two such outliers above the mean (1 in wave 2 and wave 3) to a value 3 standard deviations above the mean (using the DescTools package in R Signorell et al. (2020)).

2.4.2. Control trials

Control trials were visually matched to the experimental trials and followed a similar procedure. Any social components were removed from the control trials, such that participants were instructed to select a certain number (instead of making a trusting decision) and played these trials by themselves (without a social interaction partner).

Figure 1. **Example trial of the Trust Game.** Participants played 27 experimental and 27 control trials. Corti, the Trustee, returned 100%, 75%, or 50% of the investment.

2.5. MRI data acquisition

Magnetic resonance images were obtained using a 3.0 Tesla Philips Ingenia CX MRI scanner equipped with a 32-channel-phase array head coil (Spinoza Centre for Neuroimaging; Philips Medical Systems, Best, The Netherlands). First, a T1-weighted structural image was obtained using a three-dimensional fast field echo sequence (voxel size = 1 mm isotropic, TR = 8.2 ms; TE = 3.7 ms; flip angle = 8°; matrix 240 x 188 mm; FOV = 240 x 188 x 220 mm; 220 slices in total). Next, during the Trust Game, 494 functional images were obtained using a two-dimensional echo planar imaging-sensitivity encoding (EPI-SENSE) during one functional scan (voxel size = 3 mm isotropic; repetition time [TR] = 2000 ms, echo time [TE] = 27.63 ms; flip angle = 76.1°; matrix 80 x 80; field of view [FOV] =

240 × 240 × 121.8 mm; ascending sequential slice acquisition; 37 slices of 3.0 mm with a 0.3 mm gap). The task lasted approximately 17 minutes.

2.6. fMRI data pre-processing

fMRI preprocessing and analyses were performed with SPM12 software (<https://www.fil.ion.ucl.ac.uk/spm/doc/>). To correct for motion, subjects' functional images were realigned to a mean reference scan. To correct for slice-timing acquisition, we used the middle slice for reference. Subjects' structural images were coregistered to their mean functional image obtained with realignment. To obtain parameters for normalization, tissue probability maps tailored to the age and sex distribution of our sample at wave 1 were generated using the CerebroMatic toolbox, and used for segmentation of the coregistered structural image (Wilke et al., 2017) (template created by (van Buuren et al., 2020). Third, using the normalization parameters obtained with segmentation, all functional and structural images were normalized to MNI stereotaxic space. Next, functional images were smoothed using a low-pass Gaussian filter at 6 mm full-width-half-maximum. Scan sessions during which absolute motion parameters (translation and rotation) exceeded one voxel size (3 mm) were excluded from analyses.

Quality checks were done after normalizing the neuroimaging data. As part of the quality check, we inspected temporal signal-to-noise ratios (tSNR) in the selected ROIs. A-priori, we determined that, on the group-level, an entire ROI would be excluded from the analyses when mean tSNR would be below 50 (van Buuren et al., 2021); on the subject level, we would exclude subject's data of a particular ROI when tSNR of that ROI would be 3 SDs below mean tSNR. Based on these criteria, no ROIs nor subject-specific contrast-values were omitted from analyses (mean tSNRs ranges were 64.13-85.29 at wave 1, 69.18-90.52 at wave 2, and 65.07-91.25 at wave 3)

2.7. FMRI Data Analysis

In the general linear model (GLM), we modeled four regressors of interest: the experimental investment and repayment phase and the control investment and repayment phase. The duration of the experimental and control investment regressors was modeled as response duration. The duration of the experimental and control repayment regressors was modeled as the duration of 5500 ms. A regressor of no-interest was added consisting of the presentation of the cue screen at the start of the trial (1000 ms) and the “waiting” screen showing Corti making its decision or its control trial equivalent (1000-5000 ms). These regressors were modeled with a box-car function with a canonical hemodynamic response function (Friston et al., 1995). Furthermore, six motion parameters obtained with realignment were added as regressors of no-interest to remove effects of motion. Additionally, a high-pass filter with a cut-off of 128 seconds was added to remove low frequencies. Next, for each subject three contrast images were created for the investment phase and for the repayment phase, by contrasting the experimental and control trials of each phase to the implicit baseline and to each other. Finally, we inspected whether the ROIs were covered by the implicit functional masks of the first level analyses of participants who would be included in the whole brain factorial analysis of variance (ANOVA) (reported in the Supplementary Materials). All ROIs were included in the implicit functional masks.

2.8. Regions of interest

We used an ROI approach to conduct our main longitudinal neuroimaging analyses. We selected the (a) mPFC, (b) bilateral ventral striatum, and (c) left AI extending to the IFG as ROIs based on Van Hoorn et al. (2019), and (d) right dorsal striatum (caudate) based on Bellucci et al. (2017). First, we selected MNI coordinates of the cluster maximum reported in the meta-analyses (Bellucci et al., 2017; Van Hoorn et al., 2019), or the first two local maxima in case of multiple sub-clusters. This resulted in MNI coordinates of two local

maxima for the mPFC cluster (mPFC and ACC), two for the left AI/IFG cluster (AI and IFG), two for the ventral striatum cluster (left and right ventral striatum), and one for the right dorsal striatum cluster. Second, using the MarsBaR toolbox (Brett et al., 2002), we built 8- or 5-mm spheres for cortical and subcortical regions, respectively. This resulted in seven ROIs: mPFC, dACC, left AI, left IFG, and left and right ventral striatum, and right dorsal striatum. The spheres of the left AI and IFG were adjacent and largely overlapping, therefore we only included the sphere around the overall cluster maxima (left AI). In total we included six ROIs: dmPFC, dACC, left AI, left ventral striatum, right ventral striatum, and right dorsal striatum (Table 1; Figure 2). We performed this procedure before preregistering the study.

Using the MarsBaR toolbox (Brett et al., 2002), mean contrast estimates from the selected ROI were extracted for six contrasts of interest. To examine ROI activity underlying trust, we compared activity in experimental trials with control trials. To do so, when examining whether ROI activity was substantially higher on a within-person level, we extracted mean contrast estimates for experimental trials vs. baseline and control vs. baseline for the investment and repayment phase separately (i.e., investment phase [experimental > baseline]; investment phase [control > baseline]; repayment phase [experimental > baseline]; repayment phase [control > baseline]). Furthermore, when examining longitudinal changes in ROI activity, we examined experimental vs. control contrasts for the investment and repayment phase separately (i.e., investment phase [experimental > control] and repayment phase [experimental > control]).

A-priori, we determined that we would exclude participants if their ROI contrast estimates would be an extreme outlier (> 3 SDs from the mean) for the majority of the ROIs estimated for the investment phase [experimental > control] and repayment phase [experimental > control] contrasts (2 contrasts x 6 ROIs = 12 estimates within waves). Within wave 1, 2, and 3, there were 4, 5, and 3 participants, respectively, who were an

outlier in 1 or 2 ROI contrast estimates. In conclusion, no participants were excluded based on this criterion.

Table 1. **Selected regions of interest (ROIs).** L = left, R = right, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, IFG = inferior frontal gyrus.

ROI	Hemisphere	MNI coordinates (x, y, z)	Size of sphere (mm)	Based on (Reference)
mPFC	-	6, 42, 15	8	Van Hoorn et al. (2019)
dACC	-	3, 27, 27	8	Van Hoorn et al. (2019)
AI	L	-39, 18, 0	8	Van Hoorn et al. (2019)
IFG	L	-36, 27, -9	excluded	Van Hoorn et al. (2019)
Ventral striatum	L	-6, 12, -6	5	Van Hoorn et al. (2019)
Ventral striatum	R	9, 9, -9	5	Van Hoorn et al. (2019)
Dorsal striatum	R	12, 18, -4	5	Bellucci et al. (2017)

Figure 2. **Selected regions of interest (ROIs).** Yellow = left hemisphere, red = right hemisphere. dACC = dorsal medial prefrontal cortex, mPFC = medial prefrontal cortex.

2.9. Statistical model-building procedure

Because of the longitudinal nature of the current study, data is nested within participants. Therefore, we built mixed models using the *nlme* package (Pinheiro et al., 2020) in R (R Core Team, 2020), which allows intercepts to vary across participants. Related figures were produced with *ggplot2* (Wickham, 2009) or *effects* (Fox, 2003). We started the model-building procedure with a “null” model in which the outcome variable was predicted by a fixed and random intercept parameter only. Next, with a step-wise method, we increased the complexity of the model by extending it with new parameters. We used the maximum-likelihood method to estimate the model parameters.

Outcome and predictor variables were added to the model the following ways. Outcome variables were participants’ mean investment within a wave, investment on individual trials (extension of the analysis with mean investment as outcome variable), or ROI contrast estimate within wave. With regards to covariates and predictors, sex was dummy-coded (females = 1 and males = 0), and wave number zero-centered such that wave 1, 2, and 3 were recoded into -1, 0, and 1, respectively. We also zero-centered experimental trial number, such that it ranged from -13 to 13. Furthermore, experimental and control condition were dummy-coded into 1 and 0, respectively.

2.9.1. How does trusting behavior change across early adolescence?

To test whether trusting behavior involving an uncooperative social partner decreased across adolescence, we examined linear longitudinal changes in trusting decisions across the three waves. For the confirmatory analysis, the outcome variable was participants’ mean investment within a wave. We used a two-level model where mean investments were nested within participants. We extended stepwise from a model with only fixed and random intercept parameters, adding (in turn); (i) a main effect of covariate sex (ii) a main effect of predictor wave, (iii) a random slope of wave, and (iv) a [sex × wave] interaction.

In addition to the preregistered confirmatory analysis, we extended this two-level model to a three-level model, in which behavior on individual experimental trials (4119 data points) were nested within wave and participant (160 sessions of 77 participants). In this model, the outcome variable was investment on individual trials. We adopted the same model-building procedure as the preregistered 2-level analysis, in which “wave” was treated as the main predictor. The only difference from the model-building procedure used for the preregistered confirmatory analysis, is the addition of trial number as a covariate. Therefore, the null model with only random and fixed intercept parameters was extended stepwise by adding (i) covariates of sex and experimental trial number, (ii) linear predictor wave, (iii) random slope of wave, and finally (iv) interactions between sex, experimental trial number, and wave.

2.9.2. Are the ROIs involved in the investment and repayment phase?

Next, we tested whether activity was significantly higher in the selected ROIs (mPFC, dACC, left AI, left ventral striatum, right ventral striatum, and right dorsal striatum) in the experimental investment phase relative to the control investment phase, and in the experimental repayment phase relative to the control repayment phase. For the outcome variable, mean ROI estimates for experimental and control trials vs. baseline were used (investment phase [experimental > baseline and investment phase [control > baseline]; repayment phase [experimental > baseline] and repayment phase [control > baseline]). This resulted in three-level models in which condition (experimental and control) was nested in wave (1, 2, and 3), which was nested in participants. Using a step-wise approach, a null model including only a fixed and random intercept parameter was extended by (i) main effects of covariates sex and wave, (ii) main effect of predictor condition, (iii) interactions between condition, sex, and wave.

2.9.3. How does ROI activity change across early adolescence?

To examine how ROI activity (during to the investment and repayment phase) changed across early adolescence, we examined linear and quadratic trajectories of activity across waves, using the following contrasts: investment phase [experimental > control], and repayment phase [experimental > control]. We used two-level models (ROI contrast estimates nested within participants) to extend null models with only a fixed and random intercept parameter with (i) a main effect of covariate sex, (ii) a main linear effect of predictor wave, (iii) a random slope of wave, (iv) a parameter modeling a first-order autoregressive — AR(1) — covariance structure accounting for a random slope for wave, (v) an orthogonal polynomial quadratic term of wave, and finally (vi) wave (linear and quadratic terms) and sex interactions.

2.9.4. Model selection

We selected the best fitting model based on the Akaike Information Criterion (AIC; (Akaike, 1974)). We skipped a model-building step if the related model did not converge. For model comparisons, we did not use the log likelihood ratio significance test, because we frequently extended the model with more than one parameter. After model selection, we dropped covariates and/or random slopes from the model if they did not significantly contribute. We considered summary model results significant using varying alphas by considering the number of tests per research question. More specifically, we divided an alpha of 0.05 by the number of tests, which resulted in alphas of .05 (.05/1; “how does trusting behavior change across early adolescence?”), and .004 (.05/12; “are the ROIs involved in the investment and repayment phase?”; “How does ROI activity change across early adolescence?”). Because of the exploratory nature of the current study, we also reported results at an alpha of .05.

2.10. Whole brain group analysis

We performed secondary analyses to examine what happens at the whole brain level during the Trust Game. As these analyses cannot deal with missing data, the sample size

differed from our other longitudinal analyses ($n = 31$, 16 males, 15 females). Analyses were thresholded using a cluster-inference with a cluster-defining threshold of $p < .001$, and a cluster-probability of $p < .05$ family-wise error corrected (FWE).

First, we performed a non-preregistered analysis to inspect elevated activity on a whole brain level during the investment and repayment phase, separately. To do so, we performed a t-test for investment phase [experimental > control] and repayment phase [experimental > control]. First, with the ImCalc function in SPM, we created an “average” image of the three contrast images for each participant. We did this by summing subjects’ contrast image (“i”) obtained at wave 1, 2, and 3, which was then divided by 3, $(i_1 + i_2 + i_3)/3$. Second, we performed a t-test to examine clusters of heightened activity during experimental trials for the investment and repayment phase separately.

Second, we performed a preregistered whole brain group analysis to test longitudinal changes in activity on a whole brain level within the investment and repayment phase (separately). We conducted two flexible factorial analyses of variance (ANOVA) in SPM. Subjects’ contrast images for [experimental > control] were submitted. Subject (31 levels) and sex (2 levels) were added as between-subject factors, and wave as a within-subject factor (3 levels). We added 6 [wave $\times$ sex] interaction regressors to the statistical design ([wave 1 $\times$ male], [wave 1 $\times$ female], [wave 2 $\times$ male], [wave 2 $\times$ female], [wave 3 $\times$ male], [wave 3 $\times$ female]), which we used to specify F-contrasts testing main effects of wave (linear and quadratic) and [wave $\times$ sex] interaction effects. As this type of analysis cannot deal with between-subject main effects, a main effect of sex was not examined (Chen et al., 2014).

3. Results

3.1. How does trusting behavior change across early adolescence?

Participants invested on average 4.18 ($SD = 1.38$), 3.26 ($SD = 1.56$), and 3.09 ($SD = 2.02$) euros in the trustee at wave 1, 2, and 3, respectively. For these analyses, we used an alpha of .05. In the final model, mean investments were predicted by parameters for a random and fixed intercept, a significant main effect of wave ($b = -0.67$, $p < .001$) and significant random slope of wave ($SD = 0.81$, $p < .05$), showing that mean investments decreased with wave, and that the slopes of wave on investment varied across participants (Supplementary Figure 2). Results are described in more detail in the Supplementary Materials (Supplementary Table 2 and 3).

In addition to this preregistered analysis, we examined effects of wave when behavior on individual trials was also considered with a three-level exploratory analysis (behavior on trials nested within waves, and waves nested within participants). Figure 3 depicts investment means and error bars per experimental trial number.

Figure 3. **Investments with experimental trial number.** Means and error bars grouped by sex and wave are displayed.

“Model 3” in which the random slope of wave was added did not converge, so the random slope was omitted from the most extensive “model 4”. Model 4 showed the best fit to the data based on the AIC (Table 2). To define the final model, we removed non-significant parameters consisting of covariates from the model ($\alpha = .05$). There was no main effect of sex ($p = .55$) and no interaction effect of [sex $\times$ experimental trial number $\times$ wave] ($p = .91$). Therefore, the final model included parameters for random and fixed intercepts; main effects of wave, and experimental trial number; [sex $\times$ experimental trial number] interaction; [wave $\times$ experimental trial number interaction]; and a [sex $\times$ wave] interaction (Table 3 for a model summary). The results show a main effect of wave ($b = -0.54$, $p < .001$), a main effect of trial number ($b = -0.07$, $p < .001$), a [trial number $\times$ sex] interaction ($b = -0.01$, $p = .02$), a [wave $\times$ sex] interaction ($b = -0.24$, $p = .03$), and a [trial number $\times$ wave] interaction ($b = -0.01$, $p = .04$).

A post-hoc interrogation of the [wave $\times$ sex] interaction and [trial number $\times$ sex] interaction demonstrated that a steeper decrease with wave and trial number in males than females, main effect of wave: $b_{\text{males}} = -0.78$, $p < .001$, and $b_{\text{females}} = -0.29$, $p = .10$; trial number: $b_{\text{males}} = -0.08$, $p < .001$, and $b_{\text{females}} = -0.06$, $p < .001$ (Figure 4A and 4B, Table 4). A post-hoc interrogation of the [trial number $\times$ wave] interaction shows that all participants more steeply decreased their investments with wave, $b_{\text{wave1}} = -0.06$, $b_{\text{wave2}} = -0.08$, $b_{\text{wave3}} = -0.09$, $ps < .001$ (Figure 4C, Table 5).

Table 2. **AIC parameters with investments as outcome variable.** Df = degrees of freedom, AIC = Akaike information criterion.

model	parameter(s)	df	AIC
0	random and fixed intercept	4	19512.96
1	+ sex + trial number	6	19308.99
2	+ wave	7	19288.53
3	+ random slope of wave	-	-
4	+ wave $\times$ sex $\times$ trial number	11	19281.76

Note. Random slope of wave not included in model 4.

Table 3. **Final model summary for investments.** SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error.

All participants			
		95%-CI	
random effects	variance	lower	upper
intercept (subject level)	1.28	1.03	1.57
intercept (wave level)	0.88	0.73	1.07
fixed effects	b	SE	p
intercept	3.50	0.17	< .001
trial number	-0.07	0.00	< .001
wave	-0.54	0.11	< .001
trial number × sex	-0.01	0.00	0.02
wave × sex	-0.24	0.11	0.03
trial number × wave	-0.01	0.01	0.04

Table 4. **Model summary for post-hoc interrogations of [wave × sex] and [trial number × sex] interaction effects on investments.** SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error.

males			
		95%-CI	
random effects	SD	lower	upper
intercept (subject level)	1.18	0.89	1.57
intercept (wave level)	0.78	0.58	1.03
fixed effects	b	SE	p
intercept	3.41	0.21	< .001
trial number	-0.08	0.01	< .001
wave	-0.78	0.14	< .001
trial number × wave	-0.01	0.01	0.15
females			
		95%-CI	
random effects	SD	lower	upper
intercept (subject level)	1.38	1.00	1.90
intercept (wave level)	1.00	0.82	1.22
fixed effects	b	SE	p
intercept	3.61	0.28	< .001
trial number	-0.06	0.01	< .001
wave	-0.29	0.17	0.10
trial number × wave	-0.01	0.01	0.12

Note. Males: 2302 observations of 89 sessions of 44 participants; Females: 1817 observations of 71 sessions of 33 participants

Table 5. **Model summary for post-hoc interrogations of [trial number × wave] interaction effects on investments.** SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error.

wave 1			
		95%-CI	
random effects	SD	lower	upper
intercept (subject level)	1.29	1.06	1.56
fixed effects	b	SE	p
intercept	4.18	0.17	< .001
trial number	-0.05	0.01	< .001
trial number × sex	0.00	0.01	< .001
wave 2			
		95%-CI	
random effects	SD	lower	upper
intercept (subject level)	1.54	1.25	1.90
fixed effects	b	SE	p
intercept	3.28		< .001
trial number	-0.08		< .001
trial number × sex	-0.03		< .001
wave 3			
		95%-CI	
random effects	SD	lower	upper
intercept (subject level)	1.96	1.56	2.45
fixed effects	b	SE	p
intercept	3.10	0.31	< .001
trial number	-0.08	0.01	< .001
trial number × sex	0.00	0.01	0.94

Note. Wave 1: 1624 observations of 65 participants; wave 2: 1379 observations of 53 participants; wave 3: 1116 observations of 42 participants.

Figure 4. **Predicted investments with wave and experimental trial number.** Solid lines represent predicted values and the ribbon the 95%-confidence interval.

3.2. ROI descriptives and correlations

Descriptives of the ROI experimental > control estimates can be found in Supplementary Table 4. Correlations between ROI experimental > control estimates are visualized in Supplementary Figure 3 and, as expected, indicate positive associations between mPFC and dACC (and to some extent also the left AI), and between the various striatum clusters, during both the investment and repayment phases.

3.3. Are the ROIs involved in the investment and repayment phase?

3.3.1. Investment phase

Table 6 shows the AICs for each ROI, and Table 7 the final model parameters. We used a corrected alpha of .004. Supplementary Figure 4 depicts the predicted values of the ROI contrast estimates and Supplementary Figure 5 individual ROI contrast estimates.

3.3.1.1. mPFC. “Model 3”, the most extensive model, showed the best fit with the data as indicated with the lowest AIC. Next, we examined whether non-significant covariate parameters should be omitted from the final model (corrected alpha = .004). Main effects of sex ($p = .36$) and wave ($p = .37$), as well as [condition $\times$ sex] ($p = 0.12$), [condition $\times$ wave] ($p = .02$), [sex $\times$ wave] ($p = .65$), and [condition $\times$ sex $\times$ wave] ($p = .75$) interactions were omitted from the model. The final model for mPFC contrast estimates consisted of parameters for a fixed and random intercept and fixed parameter of condition. The final model shows a significant effect of condition ($b = 0.39$, $p < .001$), indicating higher mPFC contrast estimates in the experimental than the control condition.

3.3.1.2. dACC. “Model 3”, the most extensive model, also showed the best fit on the data for the dACC contrast estimates (as indicated by the lowest AIC). Next, we omitted non-significant covariate parameters from the model (corrected alpha = .004). Main effects of sex ($p = .08$) and wave ($p = .54$), as well as [condition $\times$ sex] ($p = 0.23$), [condition $\times$ wave] ($p = .02$), [sex $\times$ wave] ($p = .05$), and [condition $\times$ sex $\times$ wave] ($p = .87$) interactions were omitted from the model. The final model for dACC contrast estimates consisted of

parameters for a fixed and random intercept and fixed parameter of condition. The final model shows a significant effect of condition ($b = 0.64$, $p < .001$), indicating higher dACC contrast estimates in the experimental than the control condition.

3.3.1.3. Left AI. For the left AI, “model 2”, in which contrast estimates were predicted by a random and fixed intercept, sex, wave, and condition, best fitted the data. We omitted main effects of sex ($p = .44$) and wave ($p = .14$) from the final model. Hence, in the final model, left AI contrast estimates were predicted by parameters of a fixed and random intercept and fixed parameter of condition. The regression coefficient of condition suggests higher contrast estimates in the experimental condition than control condition ($b = 0.16$, $p = .01$), however this effect does not survive correction for multiple comparisons.

3.3.1.4. Left ventral striatum. “Model 2” best fitted left ventral striatum contrast estimates, which included a random and fixed intercept, wave, and condition. Next, we omitted main effects of sex ($p = .29$) and wave ($p = .89$) from the final model. Hence, in the final model, left ventral striatum contrast estimates were predicted by fixed and random intercepts and a fixed effect of condition. The regression coefficient of condition suggests higher contrast estimates in the experimental condition than control condition ($b = 0.15$, $p = .01$), however this effect does not survive correction for multiple comparisons.

3.3.1.5. Right ventral striatum. Similar to the model building procedure of the left ventral striatum contrast estimates, “model 2” also fitted right ventral striatum contrast estimates best. Main effects of sex ($p = .96$) and wave ($p = .92$) were absent and omitted from the final model. Thus, in the final model, right ventral striatum contrast estimates were predicted by fixed and random intercepts and a fixed effect of condition. The regression coefficient of condition indicates higher contrast estimates in the experimental condition than control condition ($b = 0.18$, $p < .001$).

3.3.1.6. Right dorsal striatum. For the right dorsal striatum contrast estimates, ‘model 2’ best fitted the data. After main effects of sex ($p = .19$) and wave ($p = .78$) were

omitted, the final model consisted of fixed and random intercepts and a fixed effect of condition. The final model shows a significant effect of condition ($b = 0.32$, $p < .001$), indicating higher right dorsal striatum contrast estimates in the experimental than the control condition.

Table 6. **AIC parameters with investment phase ROI as outcome variable and condition as main predictor.** Df = degrees of freedom, AIC = Akaike information criterion.

model	parameter(s)	df	mPFC	dACC	left AI	left VS	right VS	right DS
			AIC	AIC	AIC	AIC	AIC	AIC
0	random and fixed intercept	4	684.73	880.11	794.40	647.82	579.97	688.78
1	+ sex + wave	6	685.77	873.04	793.33	650.65	583.96	690.95
2	+ condition	7	648.64	813.69	788.90	645.84	572.84	667.76
3	+ condition x sex x wave	11	647.74	808.85	791.85	650.06	576.80	673.65

Table 7. **Final model summary for investment phase ROI with condition as main predictor.** SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error.

		SD	99.6%-CI	
			lower	upper
mPFC	random effects			
	intercept (subject level)	0.47	0.33	0.66
	intercept (wave level)	0.39	0.22	0.58
	fixed effects	b	SE	p
	intercept	0.18	0.07	0.011
	condition	0.39	0.06	< .001
		SD	99.6%-CI	
			lower	upper
dACC	random effects			
	intercept (subject level)	0.65	0.46	0.91
	intercept (wave level)	0.36	0.19	0.69
	fixed effects	b	SE	p
	intercept	1.08	0.10	< .001
	condition	0.64	0.07	< .001
		SD	99.6%-CI	
			lower	upper
left AI	random effects			
	intercept (subject level)	0.63	0.42	0.93
	intercept (wave level)	0.49	0.33	0.73
	fixed effects	b	SE	p
	intercept	1.23	0.10	< .001

	condition	0.16	0.06	0.012
			99.6%-CI	
	random effects	SD	lower	upper
left VS	intercept (subject level)	0.15	0.01	1.58
	intercept (wave level)	0.47	0.34	0.67
	fixed effects	b	SE	p
	intercept	-0.13	0.06	0.026
	condition	0.15	0.06	0.009
			99.6%-CI	
	random effects	SD	lower	upper
right VS	intercept (subject level)	0.21	0.06	0.71
	intercept (wave level)	0.40	0.27	0.58
	fixed effects	b	SE	p
	intercept	-0.13	0.05	0.013
	condition	0.18	0.05	< .001
			99.6%-CI	
	random effects	SD	lower	upper
right DS	intercept (subject level)	0.37	0.22	0.61
	intercept (wave level)	0.28	0.13	0.59
	fixed effects	b	SE	p
	intercept	0.21	0.07	0.002
	condition	0.32	0.06	< .001
			99.6%-CI	

3.3.2. Repayment phase

Table 8 shows the AICs for each ROI, and Table 9 the final model parameters. We used a corrected alpha of .004. Supplementary Figure 6 depicts the predicted values of the ROI contrast estimates and Supplementary Figure 7 individual ROI contrast estimates.

3.3.2.1. mPFC. For the mPFC contrast estimates, “model 2” — the null model plus main fixed effects of sex, wave, and condition — was the best fitting model as indicated by the lowest AIC. Next, non-significant covariate parameters of sex ($p = .92$) and wave ($p = .09$) were omitted from the model. In the final model, mPFC contrast estimates were predicted by fixed and random intercepts and a fixed effect of condition. The final model demonstrated a significant main effect of condition ($b = 0.26$, $p < .001$), indicating higher mPFC contrast estimates in the experimental than control condition.

3.3.2.2. dACC. “Model 2” best fitted the dACC contrast estimates. After omitting non-significant main effects of sex ($p = .02$) and wave ($p = .03$) (corrected alpha = .004), the final model included fixed and random intercept effects and a main effect of condition. Results demonstrated a main effect of condition ($b = 0.27$, $p < .001$), indicating higher dACC contrast estimates in the experimental than control condition.

3.3.2.3. Left AI. For left AI contrast estimates, “model 2” had the lowest AIC. After omitting non-significant main effects of sex ($p = .78$) and wave ($p = .79$), the final model included fixed and random intercept effects and a main effect of condition. Results show a main effect of condition ($b = 0.31$, $p < .001$), indicating higher left AI contrast estimates in the experimental than control condition.

3.3.2.4. Left ventral striatum. The most extensive model, “model 3”, was the best fitting model for left ventral striatum contrast estimates. After omitting non-significant covariate parameters (corrected alpha = .004) of sex ($p = .23$), wave ($p = 1.00$), [condition $\times$ sex] ($p = .18$), [sex $\times$ wave] ($p = .37$), and [condition $\times$ sex $\times$ wave] ($p = .89$), the final model comprised fixed and random intercepts, a main effect of condition ($b = -0.10$, $p < .001$), and a [condition $\times$ wave] interaction effect ($b = 0.07$, $p < .001$). A main effect of condition indicates that left ventral striatum contrast estimates were higher in the control condition than the experimental condition. A post-hoc interrogation of the [condition $\times$ wave] interaction effect shows that this effect is most pronounced at wave 1 ($b = -0.18$, $p < .001$), less pronounced at wave 2 ($b = -0.09$, $p = .0044$ [closely approaches significance at our corrected threshold of $p < .004$]), and absent at wave 3 ($p = .30$).

3.3.2.5. Right ventral striatum. The model comparison pointed to “model 1” (the null model extended by covariates) as the best model. However, covariates sex ($p = .08$) and wave ($p = .11$) were non-significant, and omitted from the final model. The final model comprised a random and fixed intercept and a (non-significant) effect of condition ($p = .96$),

indicating no differences in right ventral striatum contrast estimates for the control and experimental condition.

3.3.2.6. Right dorsal striatum. “Model 3”, the most extensive model, was the best fitting model for right dorsal striatum contrast estimates. All covariate parameters were non-significant at our corrected threshold ($\alpha = .004$) and omitted from the final model: sex, $p = .05$, wave, $p = .95$, [condition $\times$ sex], $p = .51$, [condition $\times$ wave], $p = .007$, [sex $\times$ wave], $p = .72$, and [condition $\times$ sex $\times$ wave], $p = .76$. In the final model, right dorsal striatum contrast estimates were predicted by fixed and random intercept parameters and a fixed main effect of condition ($b = 0.10$, $p < .001$), showing that contrast estimates were higher in the experimental than control condition.

Table 8. AIC parameters with repayment phase ROI as outcome variable and condition as main predictor. Df = degrees of freedom, AIC = Akaike information criterion.

			mPFC	dACC	left AI	left VS	right VS	right DS
model	parameter(s)	df	AIC	AIC	AIC	AIC	AIC	AIC
0	random and fixed intercept	4	156.89	270.33	249.63	30.53	-63.79	4.19
1	+ sex + wave	6	157.91	268.03	253.47	27.99	-70.09	-0.86
2	+ condition	7	67.73	195.63	147.55	-1.91	-68.10	-24.18
3	+ condition $\times$ sex $\times$ wave	11	74.32	200.04	150.07	-6.43	-67.69	-24.38

Table 9. Final model summary for repayment phase ROI with condition as main predictor. SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error.

		SD	99.6%-CI	
			lower	upper
mPFC	random effects			
	intercept (subject level)	0.14	0.08	0.26
	intercept (wave level)	0.14	0.09	0.24
	fixed effects	b	SE	p
	intercept	-0.17	0.03	< .001
	condition	0.26	0.02	< .001
dACC			99.6%-CI	

		SD	99.6%-CI	
			lower	upper
	random effects			
	intercept (subject level)	0.16	0.08	0.33
	intercept (wave level)	0.20	0.14	0.31
	fixed effects	b	SE	p
	intercept	-0.18	0.03	< .001
	condition	0.27	0.03	< .001
left AI	random effects	SD	lower	upper
	intercept (subject level)	0.18	0.11	0.31
	intercept (wave level)	0.18	0.12	0.28
	fixed effects	b	SE	p
	intercept	0.00	0.03	0.95
	condition	0.30	0.02	< .001
left VS	random effects	SD	lower	upper
	intercept (subject level)	2.70e-05	8.5e-157	8.32e+147
	intercept (wave level)	0.16	0.20	0.25
	fixed effects	b	SE	p
	intercept	-0.03	0.02	0.220
	condition	-0.10	0.02	< .001
right VS	random effects	SD	lower	upper
	intercept (subject level)	0.08	0.02	0.27
	intercept (wave level)	0.16	0.11	0.23
	fixed effects	b	SE	p
	intercept	-0.06	0.02	0.002
	condition	0.00	0.02	0.963
right DS	random effects	SD	lower	upper
	intercept (subject level)	0.09	0.03	0.25
	intercept (wave level)	0.16	0.11	0.23
	fixed effects	b	SE	p
	intercept	-0.07	0.02	0.001
	condition	0.10	0.02	< .001

3.4. How does ROI activity change across early adolescence?

3.4.1. Investment phase

Table 10 shows the AICs for each ROI, and Table 11 the final model parameters. We used a corrected alpha of .004. Please note that for the majority of the model-building procedures,

the autoregressive coefficient could not be added from model 4 onwards, which most likely resulted in too complex models. Figure 5 depicts the predicted values of the ROI contrast estimates, and Supplementary Figure 8 the individual ROI contrast estimates.

3.4.1.1. mPFC. “Model 3”, the null model plus fixed main effects of sex, wave, and a random slope of wave, showed the best fit with the data as indicated with the lowest AIC. Next, we examined whether non-significant covariate parameters of sex and random slope of wave should be omitted from the final model (corrected alpha = .004). Sex was omitted from the model ($p = .07$). The final model for mPFC contrast estimates consisted of parameters for a fixed and random intercept, a fixed linear term of wave ($b = 0.20$, $p = .02$), and a random slope of wave ($SD = 0.26$, $p < .004$), indicating that there is significant variance in slopes. The fixed linear effect of wave indicates that mPFC activity increases with wave, although this effect does not survive correction for multiple comparisons.

3.4.1.2. dACC. For the contrast estimates of dACC, “model 2” showed the best fit, the null model extended with fixed main effects of sex and wave. For the final model specification, covariate sex was removed ($p = .38$). Thus, the final model comprised parameters for fixed and random intercept, and a fixed linear term of wave. Only at an uncorrected threshold do these results show a linear increase in dACC activity with wave ($b = 0.17$, $p = .03$).

3.4.1.3. Left AI. As indicated with the lowest AIC, the best model was “model 2”. After model summary inspection, the fixed main effect of covariate sex was omitted from the final model ($p = .50$). In the final model, left AI contrast estimates were predicted by a fixed and random intercept, and a non-significant linear effect of wave ($p = .09$), indicating no changes in left AI activity across waves.

3.4.1.4. Left ventral striatum. For the left ventral striatum, “model 3”, the null model extended with fixed main effects of sex, wave, and a random slope of wave, showed the best fit. For the final model specification, the non-significant fixed main effect of sex was

omitted ($p = .06$). Therefore, the final model comprised fixed and random intercept parameters, and a random and fixed linear effect of wave. Although results indicate a significant random slope of wave ($SD = 0.43$, $p < .004$), there was no significant fixed linear effect of wave ($p = .87$).

3.4.1.5. Right ventral striatum. For the right ventral striatum contrast estimates, results were similar to those of the left ventral striatum (section 3.4.1.4). “Model 3” showed the best fit, after which the non-significant fixed main effect of sex was omitted from the final model ($p = .08$). The final model therefore also comprised fixed and random intercept parameters, and a random and fixed linear effect of wave. Although there was a significant random slope of wave ($SD = 0.45$, $p < .004$), there was no significant fixed linear effect of wave ($p = .93$).

3.4.1.6. Right dorsal striatum. For the right dorsal striatum, the best fitting model was “model 3”, as indicated with the lowest AIC. In preparation of the final model specification, we inspected the model summary. A non-significant fixed main effect of sex was omitted from the final model ($p = .57$). The final model consisted of fixed and random intercept parameters, and a random and fixed linear effect of slope. Although there was a significant random slope of wave ($SD = 0.46$, $p < .004$), there was no significant fixed linear effect of wave ($p = .60$).

Figure 5. **Main effect of wave during the investment phase.** Solid lines display the predicted values and grey ribbons the 95%-confidence interval. Invest = investment phase experimental > control, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

Table 10. **AIC parameters with investment phase ROI as outcome variable and wave as main predictor.** Df = degrees of freedom, AIC = Akaike information criterion, AR(1) = first-order autoregressive covariance structure (taking a random slope of wave into account), poly(wave, 2) = orthogonal polynomial quadratic term of wave.

model	parameter(s)	mPFC		dACC		left AI		left VS		right VS		right DS	
		df	AIC	df	AIC	df	AIC	df	AIC	df	AIC	df	AIC
0	random and fixed intercept	3	366.32	3	426.81	3	394.47	3	343.13	3	307.17	3	381.25
1	+ sex	4	366.05	4	428.08	4	396.03	4	343.09	4	306.85	4	382.86
2	+ wave	5	362.21	5	424.92	5	395.00	5	344.99	5	308.81	5	384.22
3	+ random slope of wave	7	358.47	7	426.24	7	399.00	7	337.12	7	300.13	7	382.00
4	+ AR(1)	-	-	-	-	-	-	8	338.14	-	-	8	383.86
5	+ poly(wave, 2)	8	360.36	8	428.06	8	400.69	9	339.62	8	301.51	9	385.73
6	+ poly(wave, 2) × sex	10	363.92	10	432.04	10	404.19	11	342.09	10	304.31	11	388.47

Note. When model 4 could not be fitted, the AR(1) parameter was omitted from subsequent model-building steps

Table 11. **Final model summary for investment phase ROI with wave as main predictor.** SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error.

			99.6%-CI	
			lower	upper
mPFC	random effects	SD		
	intercept (subject level)	0.19	0.02	1.56
	slope (wave)	0.26	0.22	0.86
	fixed effects	b	SE	p
	intercept	0.43	0.06	< .001
	wave	0.20	0.08	0.022
dACC	random effects	SD		
	intercept (subject level)	0.54	0.32	0.89
	fixed effects	b	SE	p
	intercept	0.63	0.09	< .001
	wave	0.18	0.08	0.026
left AI	random effects	SD		
	intercept (subject level)	0.07	2.25e-10	21538133.00
	fixed effects	b	SE	p
	intercept	0.18	0.07	0.006
	wave	0.14	0.08	0.086
left VS	random effects	SD		
	intercept (subject level)	0.29	0.13	0.64
	slope (wave)	0.43	0.23	0.79
	fixed effects	b	SE	p
	intercept	0.14	0.06	0.015
	wave	-0.01	0.07	0.866
right VS	random effects	SD		
	intercept (subject level)	0.14	0.02	1.09
	slope (wave)	0.45	0.27	0.73
	fixed effects	b	SE	p
	intercept	0.18	0.05	< .001
	wave	0.01	0.07	0.933
right DS	random effects	SD		
	intercept (subject level)	0.36	0.18	0.74
	slope (wave)	0.46	0.24	0.89
	fixed effects	b	SE	p
	intercept	0.32	0.07	< .001

wave	-0.05	0.09	0.596
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3.4.2. Repayment phase

We repeated these analyses for repayment phase ROI contrast estimates. Table 12 shows the AICs for each ROI, and Table 13 the final model parameters. We used a corrected alpha of .004. Figure 6 depicts the predicted values of the ROI contrast estimates of the mPFC, dACC, left AI, and bilateral ventral striatum, and Figure 7 of the right dorsal striatum.

Supplementary Figure 9 the individual ROI contrast estimates.

3.4.2.1. mPFC. For contrast estimates of the mPFC the best model was the null model, in which mPFC contrast estimates were predicted by a random and fixed intercept only. These results indicate a non-significant effect of wave. To be able to report a (non-significant) main effect of wave, we specified a final model by extending the null model with a linear term of wave ($p = .89$).

3.4.2.2. dACC. The null model was also the best model for dACC contrast estimates, indicating a non-significant effect of wave. We built up the final model comprising a random and fixed intercept and a fixed linear effect of wave ($p = .95$).

3.4.2.3. Left AI. For the left AI, “model 3”, the null model plus a fixed main effect of sex, was the best model. However, the covariate sex effect could be removed from the final model, because it was non-significant ($p = .09$). To be able to report the non-significant effect of wave, we specified a final model comprising a random and fixed intercept and a fixed linear effect of wave ($p = .53$).

3.4.2.4. Left ventral striatum. For the left ventral striatum contrast estimates, “model 2”, the null model plus fixed effects of sex and a fixed linear effect of wave, was the best model. Non-significant covariate sex was omitted ($p = .08$). In the final model, left ventral striatum contrast estimates were predicted by random and fixed intercept and a fixed linear effect of wave. Results indicated a linear increase in left ventral striatum activity with wave ($b = 0.07$, $p < .001$). However, this increase was non-specific to trust, because activity was

higher during control trials than experimental trials (see Figure 6D, but also results under section 3.3.2.4).

3.4.2.5. Right ventral striatum. As indicated by the lowest AIC, right ventral striatum contrast estimates were best predicted by “model 3”, the null model extended with a main effect of sex ($p = .45$) and a fixed and random linear effect of wave ($p = .04$, and $< .004$ respectively). After omission of non-significant covariate sex, the final model comprised a fixed and random intercept, and a random and fixed linear effect of wave. Results indicated a significant random slope of wave ($SD = 0.15$, $p < .004$) and, significant at an uncorrected threshold only, a linear increase with wave ($b = 0.05$, $p = .04$). Similar to results obtained for the left ventral striatum (section 3.4.2.4), this increase was non-specific to trust (see Figure 6E).

3.4.2.6. Right dorsal striatum. “Model 2”, the null plus a fixed main effect of sex ($p = .45$) and a fixed linear effect of wave best explained the right dorsal striatum contrast estimates. For the final model specification, non-significant covariate sex was omitted. Therefore, the final model comprised a fixed and random intercept and a fixed linear effect of wave ($p = .0046$). These results indicate an increase in right dorsal striatum activity with wave (Figure 7). Although the p-value .0046 of the linear effect of wave does not reach significance after applying Bonferroni correction for multiple comparisons, it closely approaches the pre-set alpha of .004.

Figure 6. **Main effect of wave during the repayment phase.** Solid lines display the predicted values and grey ribbons the 99.6%-confidence interval. Repay = repayment phase experimental > control, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum.

Figure 7. **Main effect of wave on dorsal striatum activity during the repayment phase.** The solid line displays the predicted values and the grey ribbon the 99.6%-confidence interval. Repay = repayment phase experimental > control, DS = dorsal striatum

Table 12. **AIC parameters with repayment phase ROI as outcome variable and wave as main predictor.** Df = degrees of freedom, AIC = Akaike information criterion, AR(1) = first-order autoregressive covariance structure (taking a random slope of wave into account), poly(wave, 2) = orthogonal polynomial quadratic term of wave.

model	parameter(s)	df	mPFC	dACC	left AI	left VS	right VS	right DS
			AIC	AIC	AIC	AIC	AIC	AIC
0	random and fixed intercept	3	61.30	112.15	78.26	3.21	-19.25	7.46
1	+ sex	4	63.26	113.75	77.27	3.88	-17.99	8.93
2	+ wave	5	65.24	115.74	78.87	-6.14	-20.59	2.57
3	+ random slope of wave	7	67.93	119.74	81.89	-2.43	-31.50	5.40
4	+ AR(1)	8	67.24	121.72	82.02	-2.89	-29.71	7.40
5	+ poly(wave,2)	9	68.62	123.72	77.73	-1.17	-29.49	8.52
6	+ poly(wave,2) × sex	11	72.61	126.69	79.69	1.91	-26.61	12.33

Table 13. **Final model summary for repayment phase ROI with wave as main predictor.**
SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error.

			99.6%-CI	
			lower	upper
mPFC	random effects	SD		
	intercept (subject level)	0.19	0.06	0.29
	fixed effects	b	SE	p
	intercept	0.26	0.03	< .001
	wave	0.00	0.03	0.894
dACC	random effects	SD		
	intercept (subject level)	0.20	0.11	0.35
	fixed effects	b	SE	p
	intercept	0.27	0.03	< .001
	wave	0.00	0.03	0.948
left AI	random effects	SD		
	intercept (subject level)	0.14	0.07	0.29
	fixed effects	b	SE	p
	intercept	0.30	0.03	< .001
	wave	-0.02	0.03	0.534
left VS	random effects	SD		
	intercept (subject level)	0.14	0.08	0.25
	fixed effects	b	SE	p
	intercept	-0.10	0.02	< .001
	wave	0.07	0.02	< .001
right VS	random effects	SD		
	intercept (subject level)	0.13	0.08	0.20
	slope (wave)	0.15	0.10	0.24
	fixed effects	b	SE	p
	intercept	0.01	0.02	0.481
	wave	0.05	0.02	0.044
right DS	random effects	SD		
	intercept (subject level)	0.09	0.04	0.24
	fixed effects	b	SE	p
	intercept	0.11	0.02	< .001
	wave	0.06	0.02	0.005

3.5. Whole brain group analysis

First, we tested which brain regions were significantly more active during experimental trials during the investment phase with a whole brain t-test. The investment phase yielded 12 significant clusters of activation (Supplementary Table 4, Supplementary Figure 10A). Among others, these included a large cluster in the frontal cortex (including the mPFC and dACC), the bilateral caudate (dorsal striatum) extending toward the ventral striatum, and right anterior insula. Second, we repeated this analysis for the repayment phase. The repayment phase yielded significant enhanced activity in two large clusters (Supplementary Table 5, Supplementary Figure 10B). Among other regions, these clusters included the mpFC, dACC, bilateral anterior insula, and ventral and dorsal striatal regions.

We also examined whole brain longitudinal changes for [experimental > control] for the investment and repayment phase with whole brain flexible factorial ANOVAs. We examined positive and negative linear and quadratic main effects of wave, and a [sex × wave] interaction effect. The F-tests yielded no significant clusters of activity for the investment phase as well as the repayment phase.

4. Discussion

With the current three-wave neuroimaging study, we examined young adolescents' responsiveness to uncooperative behavior and its neural correlates with a-priori defined ROIs previously linked to repeated trust interactions and/or adolescents' social decision-making. We observed a decrease in trusting behavior in an unfamiliar uncooperative other across early adolescence, which supports our preregistered hypothesis that teens become more responsive to uncooperative behavior of interaction partners across early adolescence. Also confirming our hypotheses, we observed enhanced activity in the mPFC, dACC, and right dorsal striatum (plus the left AI, but this does not survive correction for multiple comparisons), during the investment phase and repayment phase of the Trust Game. Dorsal

striatum activity also increased with wave (please note that although the p-value of .0046 of this effect does not reach significance after applying Bonferroni correction for multiple comparisons, it closely approaches the pre-set alpha of .004). We could not confirm enhanced trust-related ventral striatum activity.

In addition to our preregistered confirmatory analysis of longitudinal changes in trusting behavior, we performed another examination of participants' investments across waves by also taking behavior during individual trials into account. Following findings of Lemmers-Jansen et al. (2017), we showed that all participants decreased their investments in the uncooperative other across trials (first wave data also reported in Sijtsma et al. (*submitted*)), and that this decrease was more pronounced in males than females. Furthermore, we showed that all participants decreased their investments across trials more steeply with wave, with the largest difference in slope from the first to second wave. In other words, with age, young adolescents became more proficient in adapting trust-related behavior toward an unfamiliar uncooperative partner. This fits well with prior findings showing that older adolescents were quicker in adapting their behavior to uncooperative interaction partners than younger adolescents (Lee et al., 2016; Lemmers-Jansen et al., 2017). Whereas reciprocating trust is assumed to be driven by other-oriented motivations, trust entails both self and other-oriented motivations as both the investor and interaction partner gain from trusting decisions (Cox, 2004). As such, young adolescents may adopt a more self-oriented strategy with age. All in all, these findings confirm our hypothesis that teens become more responsive to uncooperative behavior across early adolescence.

Furthermore, results of this additional examination showed that the main effect of wave also found with the preregistered confirmatory analysis (that is, the decrease of investments with wave) was more pronounced in males than females. In other words, the additional examination suggests that the overall decrease in trust in uncooperative others across early adolescence might be most strongly driven by males. In prior studies, males

tended to invest more than females when investments were multiplied, which increased their gains (Lemmers-Jansen et al., 2017; van de Groep et al., 2020; van den Akker et al., 2020). As such, although sex differences were small, males may tend to adopt a more self-oriented strategy, whereas females might have a stronger motivation to maintain social relationships (Haselhuhn et al., 2015). However, relative contributions of biological sex-related and gender-related differences (e.g., culturally defined beliefs of gender roles such as males being more instrumental and females as caring) remain unknown.

Based on meta-analyses of Bellucci et al. (2017) and van Hoorn et al. (2019) who showed which brain regions were functionally linked to repeated trust interactions and/or adolescents' decision-making in a social context, we tested the hypothesis that the mPFC, dACC, left AI, bilateral ventral striatum, and right dorsal striatum would be longitudinally involved in trusting decisions (i.e., investment phase) and processing its repayment (i.e., repayment phase). We could largely confirm this hypothesis as all ROIs, except for bilateral ventral striatum and left AI, showed increased activity during trust trials (left AI showed the same trend but did not reach significance). As such, this is the first longitudinal developmental study that confirms robust involvement of these brain regions over time during repeated social interactions involving trust. These results support the idea that (uncooperative) interactions involving trust entail social cognitive processes related to monitoring behavior and concerns regarding the self and others (mPFC-dACC; Blakemore & Mills, 2014; Krueger & Meyer-Lindenberg, 2019), detection of socially affective stimuli (AI; Krueger & Meyer-Lindenberg, 2019), and learning about the interaction partner's cooperativeness in ongoing social exchanges (dorsal striatum; Bellucci et al., 2017; Fouragnan et al., 2013; Krueger & Meyer-Lindenberg, 2019). In contrast to Bellucci et al. (2017), we did not find enhanced ventral striatum activity related to trusting decisions in the investment phase. This may suggest that the ventral striatum plays a more important role in adults than adolescents, for example in estimating certainty about an anticipated reward

following trust (Krueger & Meyer-Lindenberg, 2019). This hypothesis should be formally tested in future studies.

Next, we tested longitudinal changes across early adolescence (here: 12-15 years) in mPFC, dACC, left AI, bilateral striatum, and right dorsal striatum activity related to the investment and repayment phase. We found a linear increase in dorsal striatum activity, which resembles findings of Lemmers-Jansen et al. (2017). In the Trust Game, the dorsal striatum has been proposed to be involved in social learning processes that contribute to behavioral adjustments to trustee's repayment responses (Krueger & Meyer-Lindenberg, 2019). More generally, in adolescents, a role of the dorsal striatum has also been ascribed to learning from feedback, especially when the outcome cannot be predicted with certainty (e.g., Delgado et al., 2005; DePasque & Galván, 2017). With regards to age-related changes, dorsal striatal activity reflecting a sensitivity to learning signals has been shown to peak in late adolescence (Peters & Crone, 2017). Tentatively, our results may point to the hypothesis that dorsal striatum activity contributes to learning from social feedback across adolescence.

In addition, we observed an increase in ventral striatum activity during repayment processing with wave, but activity was not related to trust. As such, this effect may echo the developmental adolescent-specific increase in ventral striatal reward sensitivity (Schreuders et al., 2018; Silverman et al., 2015). Finally, it should be noted that we found a linear increase in mPFC and dACC activity during trusting decisions (i.e., investment phase). However, these effects should be interpreted with caution as they were only significant at trend level and might be biased towards an increase with wave, as we observed significantly higher mPFC and dACC activity during the investment phase for participants who continued their participation in the last wave than those who withdrew. These analyses should therefore be repeated in future studies.

As a secondary aim, we repeated the analyses examining neural activity on an ROI basis on a whole brain level. These analyses largely confirmed longitudinal enhanced activity in our ROIs during the investment and repayment phase. However, we could not replicate longitudinal changes in dorsal striatum activity in the repayment phase. This discrepancy is probably due to the much smaller sample size used for these analyses (31 versus 77 participants).

An important strength of the current study is its longitudinal nature spanning the developmental window of early adolescence. However, some limitations should be acknowledged. Due to feasibility reasons, participants played the Trust Game with an uncooperative partner only. Researchers may also include a cooperative partner in future longitudinal studies, which might allow for a more in-depth examination of social (learning) processes related to trust, and aid disentangling task-learning and developmental effects (for cross-sectional studies, see Fett et al., 2014a; Lemmers-Jansen et al., 2019; Lemmers-Jansen et al., 2017). Finally, participants played the Trust Game with an anthropomorphic cartoon, which allowed us to preprogram trustee behavior to be uncooperative. We chose this approach to avoid the need to deceive participants into thinking they were playing the game with a real human partner. In prior studies, participants have been found to respond similarly to human and anthropomorphic characters on a behavioral level, but it should be noted that there are indications that responses to human interaction partners on a neural level are stronger than those to anthropomorphic characters (e.g., Kegel et al., 2020; Riedl et al., 2011). Nevertheless, findings of the current studies are in line with prior Trust Game and social decision-making studies with human partners (e.g., Fett et al., 2014a; Lemmers-Jansen et al., 2017; Lemmers-Jansen et al., 2019; van den Bos et al., 2011; van Hoorn et al., 2019), suggesting that participants perceived the trustee as a human(-like) being. Although challenging, researchers may consider using a real interaction partner to examine responses to uncooperative behavior in future studies.

To summarize, we showed that teens become more sensitive to uncooperative behavior across early adolescence, as they become quicker in lowering their trust. In other words, with age, young adolescents became increasingly flexible in switching to a more adaptive self-oriented strategy in costly social interactions. Furthermore, we demonstrated robust involvement of brain regions previously linked to processing trust repayment (Bellucci et al., 2017) and adolescents' decision-making in a social context (van Hoorn et al., 2019) in social interactions with an uncooperative other across early adolescence. Finally, with age, teens increasingly yielded dorsal striatum activity when processing repayments of trust across early adolescence, which possibly reflects a social learning process. Taken together, the findings of the current study point to early adolescence as an important developmental window for social learning processes, which contribute to establishing healthy social ties.

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Author contributions

Elisabeth Schreuders: Conceptualization, data curation, formal analysis, visualization, writing — original draft **Mariët van Buuren:** Conceptualization, data curation, investigation, methodology, writing — review and editing, project administration **Reubs J. Walsh:** investigation, methodology, software, writing — review and editing

Hester Sijsma: investigation, methodology **Miriam Hollarek, and Nikki C. Lee:** investigation, methodology, writing — review and editing **Lydia Krabbendam:** Conceptualization, funding acquisition, methodology, supervision, writing — review and editing

Declaration of conflicts

None.

Data and Code availability

Codes are available here: <https://osf.io/b9mdh/>, and https://github.com/marietvbuuren/trust_longitudinal. Data cannot be made publicly available due to privacy law regulations in The Netherlands, but data will be available upon request and can be used in collaboration with one of the research team members.

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Supplementary Materials

Learning whom not to trust across early adolescence: a longitudinal neuroimaging study to
trusting behavior involving an uncooperative other

Schreuders et al.

1. Drop-outs

Before we conducted our preregistered analyses, we examined whether participants who dropped out differed from those who continued their participation. We compared a group of participants who dropped out at a subsequent wave (2 or 3) with a group of participants who participated again at that wave on wave 1 measures. To do so, we created a between-subject factor with two levels indicating drop out (1) or continued participation (0) at wave 2, and wave 3. This variable was added as a between-subject factor in the analyses to examine differences in sex (χ^2 test), age at wave 1 (independent-samples t-test), and wave 1 outcome variables, including mean investment (independent-samples t-test), and investment and repayment phase ROI contrast estimates for experimental vs. control trials (mixed analysis of variance [ANOVA] with ROI contrast estimates as within-subject factor [6 levels]).

First, we examined whether the group of participants who dropped out at wave 2 ($n = 24$) differed on *wave 1 sex* and *age* from the group of participants who continued their participation at wave 2 ($n = 60$). The group of participants who dropped out at wave 2 did not differ significantly from the group of participants that continued their participation at wave 2, χ^2 test on sex: $\chi^2(1, n = 84) = .15, p = .70$; independent-samples t-test on age: $t(53.632) = 0.11, p = .91$. Second, we examined whether the group of participants who dropped out at wave 2 ($n = 20$) differed significantly on *wave 1 outcome variables* from participants who continued their participation at wave 2 ($n = 45$). Participants who dropped out at wave 2 did not significantly differ on wave 1 mean investment, $t(35.606) = -1.04, p = .30$. Participants who dropped out at wave 2 vs. who continued their participation did not differ in wave 1 ROI activity related to the investment phase [experimental > control] contrast, $F(1,63) = 3.06, p = .09$ (Supplementary Figure 1A), nor the repayment phase [experimental > control] contrast, $F(1,63) = 0.10, p = .75$ (Supplementary Figure 1B).

We repeated these analyses for participants who dropped out at wave 3 vs. participants who continued their participation at wave 3. First, we examined whether the group of participants who dropped out at wave 3 ($n = 36$) differed on *wave 1 sex* and *age* from the group of participants who continued their participation at wave 2 ($n = 48$). Likewise, participants who did not participate at wave 3 did not significantly differ from participants who continued their participation at wave 3, χ^2 test on sex: $\chi^2(1, n = 84) = .17, p = .68$; independent samples t-test on age: $t(81.733) = 0.43, p = .67$. Second, we examined whether the group of participants who dropped out at wave 3 ($n = 31$) differed significantly on *wave 1 outcome variables* from participants who continued their participation at wave 3 ($n = 34$). Participants who dropped-out at wave 3 did not differ significantly on wave 1 mean investment, $t(59.247) = -0.32, p = .75$. However, there was a significant main effect of drop-out vs. continued participation in ROI contrast estimates for investment phase [experimental > control] contrast indicating that participants who continued their participation yielded greater activity in the ROIs, $F(1,63) = 6.47, p = .01$. An interaction between the group (drop-out vs. continued participation) and ROI factors indicated that the effect of group was not the same for each ROI, $F(5,315) = 2.32, p = .04$. The means and standard errors (plotted in Supplementary Figure 1C) indicated that participants who continued their participation had higher contrast estimates for mPFC, dACC, left AI, and right DS. Therefore, results indicating a longitudinal increase with wave in these particular ROI investment phase [experimental > control] estimates should be interpreted with caution as the data points of wave 3 may be biased. Finally, participants who dropped out at wave 3 vs. who continued their participation did not differ in wave 1 ROI activity related to repayment [experimental > control] contrast, $F(1,63) = .03, p = .86$ (Supplementary Figure 1D).

Supplementary Figure 1. **Region of interest (ROI) contrast estimates for participants who dropped out and continued participation at wave 2 or 3.** Dots represent the mean and bars the standard error. Invest = investment phase experimental > control, repay = repayment phase experimental > control, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

2. How does trusting behavior change across early adolescence?

2.1. Confirmatory (preregistered) analysis

As indicated by the lowest AIC index, “model 4” in which all parameters were added fitted the data best (Supplementary Table 1). In preparation of specifying the final model, we examined whether covariate sex and the random slope of wave contributed significantly to this model ($\alpha = .05$). Effects of sex ($p = .60$) and wave $\times$ sex ($p = .12$) were absent and removed from the model. The random slope of wave was significant with $p < .05$, 95%-confidence interval (CI) [0.50, 1.12]. Therefore, the final model for mean investments comprised a random and fixed intercept, and a main effect and random slope of wave. The final model showed a significant main effect of wave ($b = -0.67$, $p < .001$) and a significant random slope of wave ($SD = 0.81$, $p < .05$) on mean investments, showing that mean investments decreased with wave, and that the slopes of wave on investment varied across participants (See Supplementary Figure 2 for the predicted and individual values; see Supplementary Table 2 for the model summary).

Supplementary Table 1. **AIC parameters with mean investments as outcome variable.** Df = degrees of freedom, AIC = Akaike information criterion.

model	parameter(s)	df	AIC
0	random and fixed intercept	3	594.07
1	+ sex	4	596.00
2	+ wave	5	575.21
3	+ random slope of wave	7	560.16
4	+ wave $\times$ sex	8	559.92

Supplementary Table 2. **Final model summary for mean investments.** SD = standard deviation, CI = confidence interval, b = regression coefficient, SE = standard error, p = p-value.

random effects	SD	95%-CI	
		lower	upper
intercept	1.37	1.12	1.66
wave	0.81	0.57	1.16
fixed effects	b	SE	p
intercept	3.44	0.18	< .001
wave	-0.67	0.14	< .001

Figure 2. **Predicted and individual mean investments with wave.** Solid black line displays the predicted values and the grey ribbon the 95%-confidence interval. Dots represent data points and connected dots represent one participant.

3. ROI descriptives and correlations

Means and standard deviations of the investment [experimental > control] and repayment [experimental > control] estimates of the ROIs can be found in Supplementary Table 3. A visualization of correlations between ROI [experimental > control] estimates is depicted in Supplementary Figure 3.

Supplementary Table 3. **Descriptives experimental > control estimates of ROIs.**
ROI = region of interest, M = mean, SD = standard deviation.

ROI	Investment phase		Repayment phase	
	M	SD	M	SD
Wave 1				
dmPFC	0.22	0.71	0.26	0.29
dACC	0.44	0.82	0.27	0.32
left AI	0.07	0.70	0.34	0.32
left ventral striatum	0.14	0.77	-0.18	0.24
right ventral striatum	0.21	0.62	-0.05	0.21
right dorsal striatum	0.36	0.76	0.04	0.23
Wave 2				
dmPFC	0.46	0.65	0.23	0.26
dACC	0.70	0.97	0.27	0.37
left AI	0.14	0.91	0.23	0.26
left ventral striatum	0.19	0.59	-0.09	0.21
right ventral striatum	0.14	0.53	0.03	0.18
right dorsal striatum	0.34	0.67	0.13	0.23
Wave 3				
dmPFC	0.56	0.88	0.28	0.33
dACC	0.86	1.03	0.27	0.36
left AI	0.36	0.85	0.33	0.34
left ventral striatum	0.09	0.73	-0.04	0.26
right ventral striatum	0.19	0.74	0.04	0.28
right dorsal striatum	0.25	0.97	0.16	0.27

Supplementary Figure 3. **A visualization of correlations between experimental > control estimates of regions of interests.** Invest = investment phase, replay = repayment phase, corr = correlation coefficient.

4. Region of interests

4.1. Are the ROIs involved in the investment and repayment phase?

Supplementary Figure 4 and 5 show the predicted values and individual contrast estimates of [control > baseline] and [experimental > baseline] for the investment phase, respectively.

Supplementary Figure 4. **Main effect of condition during the investment phase.** solid lines display the predicted values and grey ribbons the 99.6%-confidence interval. Invest = investment phase condition > baseline, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

Supplementary Figure 5. **Region of interest contrast estimates with condition during the investment phase.** Dots represent data points and connected dots represent one participant. Invest = investment phase condition > baseline, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

Supplementary Figure 6 and 7 show the predicted values and individual contrast estimates of [control > baseline] and [experimental > baseline] for the repayment phase, respectively.

Supplementary Figure 6. **Main effect of condition during the repayment phase.** Solid lines display the predicted values and grey ribbons the 99.6%-confidence interval. Repay = repayment phase condition > baseline, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

Supplementary Figure 7. **Region of interest contrast estimates with condition during the repayment phase.** Dots represent data points and connected dots represent one participant. Repay = repayment phase condition > baseline, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

4.2. How does ROI activity change across early adolescence?

Supplementary Figure 8 and 9 show the ROI contrast estimates of [experimental > control] for the investment phase and repayment phase, respectively.

Supplementary Figure 8. **Region of interest contrast estimates with wave during the investment phase.** Dots represent data points and connected dots represent one participant. Invest = investment phase experimental > control, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

Supplementary Figure 9. **Region of interest contrast estimates with wave during the repayment phase.** Dots represent data points and connected dots represent one participant. Repay = repayment phase experimental > control, mPFC = medial prefrontal cortex, dACC = dorsal anterior cingulate cortex, AI = anterior insula, VS = ventral striatum, DS = dorsal striatum.

5. Whole brain group analysis

On a whole brain level, we performed an exploratory whole brain t-test for investment phase and repayment phase [experimental > control] contrast. Supplementary Table 4 and Supplementary Figure 10A shows clusters of activity for the investment phase and Supplementary Table 5 and Supplementary Figure 10B for the repayment phase.

Supplementary Table 4. **Whole brain clusters of activation for experimental > control during investment phase.** Thresholded at $p < .05$ family-wise error (FWE) cluster-corrected with a cluster-forming threshold of $p < .001$. Anatomical labels from Laboratory of Neuro Imaging (LONI) atlas. MNI = Montreal Neurological Institute, L = left, R = right.

voxels	t	MNI coordinates			Anatomical labels
		z	x	y	
2447	11.04	6.93	-6	30	33 L superior frontal gyrus
	10.58	6.78	12	12	63 R superior frontal gyrus
	9.83	6.52	-9	18	51 L superior frontal gyrus
667	9.52	6.41	-9	6	-3 L caudate
	8.61	6.07	15	21	3 R caudate
	8.33	5.95	-9	18	3 L caudate
316	8.44	6	-27	-93	-3 L middle occipital gyrus
	6.83	5.26	-12	-99	3 L middle occipital gyrus
	5.9	4.77	-39	-84	-6 L middle occipital gyrus
99	8.16	5.88	36	18	-9 R insular cortex
331	7.39	5.53	-3	-24	33 L cingulate gyrus
	6.3	4.99	-6	-42	24 L cingulate gyrus
	6.24	4.96	6	-42	24 R cingulate gyrus
336	7.35	5.52	6	-69	42 R precuneus
	6.29	4.98	-12	-69	36 L superior parietal gyrus
91	6.39	5.04	-33	21	-9 L lateral orbitofrontal gyrus
	4.2	3.69	-33	18	3 L insular cortex
139	6.38	5.03	36	-84	-9 R inferior occipital gyrus
	6.21	4.94	30	-93	-6 R middle occipital gyrus
	4.71	4.04	21	-99	0 R middle occipital gyrus
123	6.38	5.03	42	-63	-48 cerebellum
	5.55	4.57	36	-63	-33 cerebellum
	5.23	4.37	45	-66	-33 cerebellum
165	6	4.83	42	-63	48 R angular gyrus
	4.76	4.08	36	-60	39 R angular gyrus
94	5.85	4.74	-33	-63	-36 cerebellum
	4.88	4.15	-48	-69	-33 cerebellum
86	5.49	4.53	-33	-57	45 L angular gyrus

Supplementary Table 5. **Whole brain of activation for experimental > control during the repayment phase.** Thresholded at $p < .05$ family-wise error (FWE) cluster-corrected with a cluster-forming threshold of $p < .001$. Anatomical labels from Laboratory of Neuro Imaging (LONI) atlas. MNI = Montreal Neurological Institute, L = left, R = right.

voxels	t	z	MNI coordinates			Anatomical labels
			x	y	z	
16213	13.18	7.53	6	-30	-15	brainstem
	12.84	7.44	-33	-63	-36	cerebellum
	12.57	7.37	33	-90	-6	R middle occipital gyrus
1075	8.32	5.95	-54	18	36	L middle frontal gyrus
	8.19	5.89	-48	27	36	L middle frontal gyrus
	7.89	5.76	-27	12	54	L middle frontal gyrus

A Investment phase [experimental > control]

B Repayment phase [experimental > control]

Supplementary Figure 10. **Whole brain activity during investment and repayment phase.** Activity is overlaid on an average anatomical brain matched for subjects' age and gender. Results are shown with a cluster-defining threshold of $p < .001$, and a $p < .05$ FWE corrected cluster threshold.