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Longitudinal changes in social brain development: processing outcomes for friend and self

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Abstract

Adolescence is an important time for social development, during which friendships become more intimate and complex. In this fMRI study we tested how outcomes for friends are processed on the neural level across adolescence. Participants between 8 and 27 years of age were tested twice with a two year difference between the first (N=299) and second (N=254) time point. Participants performed a task in which they could win and lose money for themselves and their best friend. Mixed linear models revealed a linear decrease in activity in social brain regions for Friend > Self over development. These results confirm changes in the social brain network across adolescent development, we further show that individual differences are related to these neural changes.

Keywords: *Adolescence, fMRI, brain development, social cognition*

Understanding others and inferring mental states of others is critical for forming close social bonds, which is often considered a fundamental human need (Williams, 2007). Prior studies based on self-report questionnaires (Sumter, Bokhorst, Steinberg, & Westenberg, 2009), sociometric analyses (Cillessen, 2007) and laboratory tasks (Dumontheil, Apperly, & Blakemore, 2010) have reported that adolescence is an important transition period for social development, specifically for the ability to understand the intentions of others and consequences of actions for others (for a review, see Blakemore, 2008). Neuroscience studies on social information processing in adults have revealed a network of brain areas related to thinking about others (Van Overwalle, 2009). These studies have pointed out that this network of brain regions, also referred to as the social brain, includes the temporo-parietal junction (TPJ), superior temporal sulcus (STS) and midline structures including the precuneus and medial prefrontal cortex (mPFC). Most studies in adults have reported robust activity in the social brain network when thinking about others (Van Overwalle, 2009) and it was previously found that this network is more engaged when thinking about close friends (Güroğlu et al., 2008). To understand how changes in neural regions are related to changes in the adolescent social world it is important to understand neural trajectories of social brain regions.

Developmental neuroscience studies have compared thinking about the self and others in a variety of paradigms. These studies showed that activity in all regions of the social brain network changes considerably during adolescence (for a review, see Blakemore, 2008). These findings fit well with reports that show that regions in the social brain network also develop structurally during adolescence (Mills, Lalonde, Clasen, Giedd, & Blakemore, 2014). Thinking about traits of others versus traits of the self, resulted in activation in the TPJ, precuneus, and ventral mPFC (Pfeifer et al., 2013). To further investigate developmental trends over time and their relation with self-report measures we used a longitudinal design in

this study. A longitudinal design is optimized for the possibility to assess developmental trends over time as well as changes within and between individuals. The previously discussed studies have focused on thinking about others (Blakemore, 2008; Burnett, Sebastian, Kadosh, & Blakemore, 2011), whereas in real life many of our decisions involve not only thinking about others state of mind, but also involve outcomes for others. In the current study we extend the prior work on mentalizing and address two important new questions: 1) how does the social brain network process *outcomes* for the self and for others and 2) how does activation in the social brain network change over development when processing outcomes for the self and *friends*, instead of for unknown others?

The current study set out to test these questions by making two important modifications to the designs of prior studies. Firstly, in the current study, participants played a gambling task in which we focused on the *outcomes*, i.e. winning or losing money, rather than traits or intentions (Braams et al., 2013; Braams, Peters, Peper, Guroglu, & Crone, 2014). Secondly, the outcomes in the gambling task were for a best *friend* instead of an unknown other. Developmental changes for outcomes for *friends* specifically are not yet well understood (Braams et al., 2013). Participants in a continuous age range between 8 and 27 years of age were tested twice within a two-year interval. We previously found using the same task in a cross-sectional sample that social brain regions, including TPJ, precuneus and mPFC, were most strongly engaged when processing outcomes for friend relative to self (Braams et al., 2013). In the current study, we addressed the question of stability versus developmental change in activity in this network of the brain by making use of a longitudinal, rather than a cross-sectional design. In line with major changes in social development during adolescence and structural changes in the social brain (Mills et al., 2014), we expected to find developmental changes in TPJ, precuneus and mPFC. As directionality of the effect is difficult to hypothesize based on previous work, as studies have found increases (Gunther

Moor, van Leijenhorst, Rombouts, Crone, & Van der Molen, 2010; Guroglu, van den Bos, van Dijk, Rombouts, & Crone, 2011; Pfeifer et al., 2013), decreases (Blakemore, den Ouden, Choudhury, & Frith, 2007; Burnett, Bird, Moll, Frith, & Blakemore, 2009; Wang, Lee, Sigman, & Dapretto, 2006) and quadratic effects in this network (Somerville et al., 2013), we tested whether neural activation in these regions increases, decreases or shows a quadratic response over development.

Furthermore, to investigate which individual differences were related to activation in these regions, friendship quality and ratings of how much the participants thought their friend deserved to win were assessed at each time point. We tested whether changes in these self-report measures showed a relation with changes in neural activation during the task.

Method

Participants

On the first time point (T1) 299 participants participated in the study ($Mean_{age}$ = 14.15 years; SD_{age} = 3.56; $Range_{age}$ = 8.01-25.95 years; 143 males). Approximately two years later ($Mean_{time\ difference}$ = 1.99 years; $SD_{time\ difference}$ = 0.10; $Range_{time\ difference}$ = 1.66 – 2.47 years) all participants were invited to participate again for data collection for the second time point (T2). Thirteen participants indicated that they could not or did not want to participate again. Therefore, data at T2 were collected from 286 participants ($Mean_{age}$ = 15.80 years; SD_{age} = 3.54; $Range_{age}$ = 9.92 – 26.62 years; 135 males). Of the 286 participants who participated at T2, 32 participants were unable to participate in the MRI session due to braces. Written informed consent for the study (parental consent and participant assent for children and adolescents) was provided by all participants at both time points. All participants were right-handed, reported normal or corrected-to-normal vision and an absence of neurological or psychiatric impairments.

Estimated intelligence scores were obtained using four subscales of the Wechsler Adult Intelligence Scale (WAIS) for participants aged 17 and older or the Wechsler Intelligence Scale for Children (WISC) for participants aged 16 and younger. At T1 the subtests similarities and block design of the WISC or WAIS were administered, at T2 the subtests picture completion and vocabulary were administered. Different subtests were used at both measurements to avoid carry-over or learning effects from the first measurement. IQ scores and age were not correlated on both time points (T1 r (294) = -.041, p = .49; T2 r (256) = .045, p = .48).

Participants received an endowment for participation in the larger study. Adult participants received 60 euro on each time point, participants aged 12-17 received 30 euro and participants younger than 12 received 20 euro on each time point. In addition to this endowment participants could win 4, 5 or 6 euros in the fMRI task (see fMRI task description). All procedures were approved by local institutional review boards.

Data for the current study were collected at Leiden University, The Netherlands as part of a large longitudinal study named Braintime. The procedure and task design has been described in detail previously in Braams et al. (2015). Results from the first measurements have previously been published in Braams et al. (2014), and a separate longitudinal report in Braams et al. (2015).

Procedure

Participants were prepared for the testing session in a quiet room. They were familiarized with the MRI scanner with a mock scanner and by listening to recordings of the scanner sounds. Next, participants received instructions for the fMRI task and performed six practice trials of the task. Procedures were similar for the two sessions.

Experimental Design and Self-Report Measures

fMRI task. Participants played a heads or tails gambling game in which they could win or lose money (Braams et al., 2013; Braams et al., 2014; Braams et al., 2015). On each trial participants guessed whether the computer would pick heads or tails and they won when the computer selected the chosen side of the coin. Each trial started with a trial onset screen (4000 ms) during which the participant made their choice to play for heads or tails. On the trial onset screen the participants saw how much they could win or lose on that trial. Probabilities for winning were 50%. Three different distributions of coins were included; trials on which 2 coins could be won and 5 lost, trials on which 3 coins could be won or 3 lost and finally trials on which 5 coins could be won or 2 could be lost. These different distributions of coins were included to keep participants engaged in the task, but were not analyzed separately (see also Braams et al., 2013; Braams et al., 2014). Participants were informed about the different distributions of coins and were familiarized with them during the practice task. The trial onset screen was followed by a fixation screen (1000 ms) and a feedback screen, which showed whether participants won or lost on that trial (1500 ms). Trials ended with a variable jitter (1000-13200 ms), see Figure 1. Trial sequence and timing was optimized using OptSeq (Dale, 1999); see also (http://surfer.nmr.mgh.harvard.edu/optseq/). Participants were instructed that the coins won during the experiment would translate to real money at the end of the experiment. Participants received 4, 5 or 6 euro's at the end of the task. Unbeknownst to the participants, the total earnings on the task did not relate to the amount won during the task. Participants played 30 trials in the gambling game for themselves, 30 trials for their best friend and 30 trials for another person. Participants were asked before the start of the study who their best friend was and we used this name during the task. Only the trials in which participants played for

themselves and their best friend were administered at both time points and therefore only those trials are the focus of the current study.

Self-report Measures

Friendship quality. Friendship quality was assessed by an adapted version of the Friendship Quality Scale (FQS; Bukowski, Hoza, & Boivin, 1994). Participants filled out the FQS about their best friend, at home before the scanning session. The adapted FQS is comprised of 20 questions and assesses both positive and negative friendship quality. An example item for the positive scale is 'I can trust and rely upon my friend' and an example item for the negative scale is 'My friend can bug or annoy me even though I ask him not to'. Participants indicated on a 5-point scale how true this item was with (1) 'not true at all', to (5) 'very true'. Separate scores were calculated for both the positive and negative friendship quality subscales. The positive subscale consists of 13 items, therefore total scores for the positive subscale can range between 13 and 65. Higher scores on the positive friendship subscale indicate more positive friendship quality. Mean score for the positive subscale was 55.45 (SD = 6.3; range = 37-65) at T1 and 55.97 (SD = 6.0; range = 36-65) at T2. The negative subscale consists of 7 items, thus total scores for the negative subscale can range between 7 and 35. Higher scores on the negative subscale indicate more negative friendship quality. Mean score for the negative subscale was 11.5 (SD = 3.9; range = 7-26) at T1 and 12.0 (SD = 3.9; range = 7-25) at T2. In total friendship quality scores were available for 277 participants at T1 and 286 participants at T2. In total, combined fMRI and FQS ratings were available for 234 participants at T1 and 236 participants at T2. For 215 participants data was available for the FQS and fMRI task on both time points, of these participants, 87 participants (M_{age} = 14.87 , SD_{age} = 3.56) reported the same friend on the second time point and 150 participants (M_{age} = 13.91, SD_{age} = 3.21) reported a different best friend. The difference in age between those

participants who reported the same friend and those who reported a different friend was not statistically significant (t(213) = 2.07, p = .167). Furthermore, we used independent samples t-tests to compare friendship quality for participants who at T2 reported the same friend as at T1 with those who did not. Results showed that there were no differences in friendship quality between the groups for the positive (T1: t(258)=1.71, p=.088; T2: t(258)=.523, p=.601) and negative (T1: t(251)=1.573, p=.117; T2: t(251)=.313, p=.755) friendship quality scales at both time points.

Self-report ratings. After the scanning session participants indicated how much they felt that their friend deserved to win. Ratings were made on a 10-point scale ranging from (0) 'not at all' to (10) 'very much'. The mean score for this rating was 8.12 at T1 (SD = 1.8; range = 0 – 10) and 8.0 (SD = 1.8; range = 0 – 10) at T2. Ratings were available for 291 participants at T1 and 251 participants at T2. In total, combined fMRI and ratings were available for 243 participants at T1 and 233 participants at T2.

MRI Data Acquisition

Scanning was performed on a 3 Tesla Philips scanner, with a standard 32 channel whole- head coil. The functional scans were acquired using T2*-weighted echo-planar imaging (EPI) (TR= 2.2 sec, TE= 30 ms, sequential acquisition, 38 slices of 2.75 mm, field of view 220 mm, 80x80 matrix, in-plane resolution 2.75 mm). The first two volumes were discarded to allow for equilibration of T1 saturation effects. After the two functional runs, a high-resolution 3D T1- weighted anatomical image was collected (TR= 9.751 ms, TE=4.59 ms, flip angle= 8°, 140 slices, 0.875mm x 0.875mm x 1.2mm, and FOV= 224.000x168.000x177.333). Visual stimuli were displayed on a screen in the magnet bore. A mirror attached to the head coil allowed participants to view the screen. Foam inserts inside

the coil were used to limit head movement. MRI data acquisition was performed at the same scanner and all procedures were comparable at the two time points (see also Braams et al., 2014).

fMRI Preprocessing and Statistical Analyses

At T1 299 participants were included in the MRI session and at T2 254 participants were included. For fMRI-analyses, 36 participants on T1 (mean $_{age}$= 11.59, st dev $_{age}$=3.21, range $_{age}$ = 8.01-20.25) and 10 participants on T2 (mean $_{age}$ =12.68, st dev $_{age}$ = 1.94, range $_{age}$ = 10.26-15.93) were excluded for moving more than 1 voxel. An additional 14 participants on T1, and six participants on T2, were excluded for not finishing the task, technical problems, or artifacts during data collection. The final sample for fMRI analyses was therefore 249 participants on T1 and 238 participants on T2.

All data were analyzed with SPM8 (Wellcome Department of Cognitive Neurology, London). Images were corrected for slice timing acquisition and differences in rigid body motion. Structural and functional volumes were spatially normalized to T1 templates. Translational movement parameters of the included sample never exceeded 1 voxel (<3 mm) in any direction for any participant or scan. The normalization algorithm used a 12-parameter affine transform together with a nonlinear transformation involving cosine basis functions and resampled the volumes to 3mm cubic voxels. Templates were based on the MNI305 stereotaxic space. Functional volumes were spatially smoothed with a 6 mm FWHM isotropic Gaussian kernel. Statistical analyses were performed on individual subjects data using the general linear model in SPM8. The fMRI time series were modeled as a series of zero duration events convolved with the hemodynamic response function (HRF). The task was an event related design. On trial onset events were modeled separately for playing for self, friend and other. On feedback onset winning and losing for self, friend and other were

modeled. This resulted in three conditions at trial onset (self, friend, other) and six conditions at feedback onset (self win, self lose, friend win, friend lose, other win, other lose). Note that all conditions were modeled, but only self win, self lose, friend, win and friend lose are used in the analyses. Trials on which the participants failed to respond were modeled separately as a covariate of no interest and were excluded from further analyses. The modeled events were used as regressors in a general linear model, along with a basic set of cosine functions that high-pass filtered the data, and a covariate for session effects. The least-squares parameter estimates of height of the best-fitting canonical HRF for each condition were used in pair-wise contrasts. The resulting contrast images, computed on a subject-by-subject basis, were submitted to random-effects group analyses. Whole brain analyses for the contrasts Friend > Self and Self > Friend are reported in the supplementary material.

Region of Interest Selection

Region of interest (ROI) selection was based on an independent source as regions of interest in a longitudinal design may be biased towards one of the time points. That is to say when ROI selection is based on the first time point selection may be biased towards this time point. ROIs can also be biased towards stability when ROIs are selected based on a conjunction for both time points. Selection of independent ROIs ensures unbiased selection. In this study ROIs were selected based on an independent meta-analysis (Van Overwalle & Baetens, 2009). Coordinates were originally reported in Talairach space and were transferred to MNI space with the tal2icbm_spm.m script, available from http://www.brainmap.org/icbm2tal/. Reported coordinates from the meta-analysis were used to create 6 mm spheres around the peak voxel reported. A total of four regions of interest were used: the left TPJ (MNI -55 -54 27), right TPJ (MNI 55 -54 27), precuneus (MNI 2 -58 46) and a ventral medial prefrontal cortex cluster (MNI 1 57 12), see Figure 2. We extracted

parameter estimates from these clusters. These parameter estimates were used in subsequent analyses.

Control region: visual cortex.

To investigate whether the developmental results are specific to the ROIs that were selected based on the meta-analysis we included a control ROI analysis. We used the Occipital Mid area, left and right, derived from the marsbar anatomical regions for this purpose. We performed the same model fitting procedure as was used for the other ROIs. Results showed no developmental effects in the occipital mid area. A full description of these results can be found in the supplemental materials.

Mixed Model Building Procedure

Analyses on ROI values were performed using a mixed models approach in R (R Core Team, 2014) and package *nlme* (Pinheiro, Bates, DebRoy, & Sarkar, 2013). Mixed models (also known as hierarchical linear modeling, multilevel modeling or random effects modeling) allow for data hierarchies as observed in longitudinal datasets. Time points within a longitudinal dataset are nested within participants and a mixed models approach recognizes this type of data dependency. Mixed models were used to determine general patterns, i.e. grand mean trajectories, of age-related change (linear or quadratic) and within these general patterns, assess individual variation in intercepts (i.e. starting points) and slopes (i.e. pattern of change over time). These goals concur with (i) the inclusion of fixed effects that account for a grand-mean trajectory thereby capturing the mean developmental pathway of the full sample and (ii) random effects that can test for individual variation in intercepts and slopes.

To test developmental effects, all mixed-models followed a formal model-fitting procedure. That is, we started with a null model that included a fixed and a random intercept, to allow for individual differences in starting points and account for the repeated nature of the

data. The null model with random intercept was compared against two additional models that tested the grand mean trajectory of age. These models were created by adding two polynomial terms (linear and quadratic; mean-centered) for age to the null model. Linear effects of age indicate a monotonic change over age, and quadratic effects of age indicate an adolescent-specific effect, in which adolescent responses differ from those of children and adults (Somerville et al., 2013). Akaike Information Criterion (AIC; Akaike, 1974) values as well as Bayesian Information Criterion (BIC; Schwarz, 1978) values were compared between the null model and each of the models with a polynomial term for age to test whether a null model, linear or quadratic model best explained the relation between the dependent measure and age. AIC and BIC are standardized model-fit metrics that allow for comparison of models. Preferred models have lower AIC and BIC values. To formally compare whether models with lower AIC and BIC values were significantly better, we compared models differing one degree of freedom (i.e. null and linear, and linear and quadratic) using a log likelihood ratio test. Level of significance used for the log likelihood test was $p<.05$. We expected linear and quadratic age effects based on previous literature (Somerville et al., 2013). To test whether any of the ROIs showed cubic effects we also fitted models with a cubic term for age. None of the ROIs showed a cubic trajectory over age and cubic models are therefore not further described.

The next step in the model-building procedure was to determine whether there were significant individual differences in the effects of age by adding a random-slope of age to each of the best-fitting models. A random-slope of age allows the inclusion of different beta-coefficients for each subject. A significant random-slope term would indicate significant individual differences for the effect of age. The significance of the random terms was determined via AIC and BIC evaluation for improvement in model fit, as well as a log

likelihood test. Random slopes were not significant for any of the fitted models, and therefore random slopes are not discussed in the results section.

All models were fit with full information maximum likelihood estimates. A fitted mixed-model with only a mean- centered linear term of age (referred to as Age Linear) reads in formal notation:

Level 1:

$$Y_{ti} = \pi_{0i} + \pi_{1i} * (\text{Age Linear})_{ti} + e_{ti}$$

Level 2:

$$\pi_{0i} = \gamma_{00} + r_{0i}$$

$$\pi_{1i} = \gamma_{10} + r_{1i}$$

In which Y_{ti} represents, for instance, neural activation in a region of interest at the t'th timepoint for the i'th individual. Substitution of the second level model into the first level model produces the intgrated model that was fit to the data. As age is mean-centered, the fixed intercept γ_{00} represents grand mean neural activation level at the mean age of the sample. γ_{10} represents the grand mean slope (main effect) of age (linear). The random intercept (r_{0i}) captures between-participant variance in the intercept (e.g., individual differences in the mean neural activation level at the mean age of the sample), and individual differences in the slope (r_{1i}) (i.e., the change in neural activation level over age). Finally, the variance of e_{ti} denotes within-participant variance. We fit separate models for each region of interest and describe the best fitting model for each region in the results section.

Results

Stability of Neural Activity across Time Points

Intra Class Correlations (ICC) over time were calculated to investigate stability responses across time points. ICC values were calculated using SPSS with a two-way mixed effects model with absolute agreement, and average measures are reported. ICC values for the friendship quality questionnaire and the self-report rating were relatively high with values ranging between .368 and .697. To calculate ICC values for neural activity parameter estimates were extracted from all ROIs. ICC values were low, ranging between 0.054 and 0.356. Values below .4 are considered low in test-retest stability as described by Cicchetti (1981). Thus, these values indicate considerable change across time points in neural activity. All ICC values are reported in Table 1.

Developmental Effects

We used a linear mixed modeling approach to test for grand mean trajectories of age for each ROI. We used the contrast value for the contrasts Friend > Self, Friend > Fixation and Self > Fixation. We tested linear and quadratic effects of age for each of the ROIs separately. AIC and BIC values were used to guide model selection and a formal model comparison using a log likelihood ratio test was used to determine which model showed the best fit.

For the contrast Friend > Self the developmental trajectories for left and right TPJ, and precuneus were best described by a negative linear relation with age (see Figure 3 for predicted model plots for each of the clusters, see Supplementary Figure 2 for raw data, see Table 2 for an overview of AIC and BIC values and Table 3 for a description of the fitted models). This suggests that the difference in activation in these areas when processing outcomes for Friend versus Self decreases over age. For the ventral mPFC cluster, the best

fitting model was a null model. This indicates that there are no developmental changes in the relative difference between activation for friend and self in this cluster.

To test if developmental changes were accounted for by Friend or Self changes, follow up comparisons for Friend > Fixation and Self > Fixation were performed. These analyses showed that separate developmental patterns were observed for these conditions. First, for the precuneus, age related decreases were found for both Friend > Fixation and for Self > Fixation, but the developmental pattern was more pronounced for Friend > Fixation. Second, for the left TPJ, Friend > Fixation remained stable across age, but Self > Fixation activation increased across development. Thus, young adolescents recruited the left TPJ more for outcomes for Friend, whereas adults recruited the left TPJ for both outcomes for Friend and for Self. For the right TPJ the best fitting model for both Friend > Fixation and Self > Fixation was a null model, indicating no developmental changes. For ventral mPFC the best model for Friend > Fixation and Self > Fixation was a null model, indicating no change in activation over development in these post hoc analyses. See Figure 3 for predicted model plots for all areas.

Correlations with Self-Report Measures

Next we addressed the question whether neural activity patterns were modulated by self-report measures. Firstly, we tested whether there was a relation with age for self-reported friendship quality as measured with the Friendship Quality Scale and the self-report ratings in which participants indicated how much they felt their friend deserved to win. We also tested whether friendship quality was related to the self- report rating of how much participants thought their friend deserved to win. Secondly, we used linear mixed models to test which neural regions (left and right TPJ, precuneus, and ventral mPFC) showed a relation with the self-report measures. To correct for developmental effects each of these models was fit with a

linear term for age, even when age effects were not significant. In these models the neural activation was the dependent variable, age and the self-report measure were used as independent variables.

Friendship quality. There was no significant relation between the friendship quality scale (positive or negative) and age. Positive friendship quality was positively related to the self-report rating of how much participants thought their friend deserved to win, this model is corrected for age (β=29.85, t=5.36, p<.001). Negative friendship quality was negatively related to the self-report rating of how much the participant thought their friend deserved to win, again this model is corrected for age (β =-13.11, t=-3.48, p<.001). There was no significant relation between FQS and neural recruitment for contrasts of interest.

Self-report rating. The rating for how much a friend deserved to win did not show a relation with age (p=.329). A positive linear relation was found between this rating and the contrast values for Friend > Self for precuneus (β = 6.88, $t_{(195)}$= 2.06, p=.041) and the ventral mPFC (β = 10.01, $t_{(195)}$=2.70, p=.007). The models with the self-report rating included provided a better fit to the data compared to the models with only a regressor for age (Precuneus: AIC age model: 2499, AIC age and self-report rating model 2497, loglikelihood ratio p-value .039; vMPFC: AIC age model: 2598, AIC age and self-report rating model 2592, loglikelihood ratio p-value .007). In other words, those participants who indicated that they felt that his or her friend deserved to win most showed the highest activation in the precuneus and ventral MPFC when receiving outcomes for a friend compared to outcomes for his or herself. The additional effect of self-report rating above age was not significant for both TPJ clusters: TPJ left (p=.132), TPJ right (p=.145).

Discussion

Although behavioral changes in social reasoning have been well documented in the past decades (Cillessen, 2007; Steinberg & Morris, 2001), only recently have studies reported extensive changes in neural activity of social brain areas during adolescence (Blakemore, 2008; Pfeifer & Peake, 2012). In this study we tested developmental patterns of brain responses to processing outcomes for friends and self. The current study provides a novel contribution to this growing literature by (1) investigating how adolescents process outcomes for others, (2) by focusing specifically on outcomes for best friends rather than distant or unknown others, and (3) by using a longitudinal design in a large study with age samples across the whole range of adolescence.

Developmental patterns

To answer whether variability in neural activity over time could be explained by age related changes, linear mixed models were implemented to test for linear and non-linear trajectories of age (see also Braams et al., 2015). Results showed that neural responses to outcomes for friends and outcomes for self in social brain regions (consisting of TPJ, precuneus and ventral mPFC) became increasingly similar with age. In other words, in early adolescence there was a relatively large differentiation between outcomes for friend and self, which became smaller in late adolescence and early adulthood. These findings suggest that when adolescents are developing their self-concept and identity (Crocetti, Rubini, Branje, Koot, & Meeus, 2015; Pfeifer & Peake, 2012), they may distinguish more between consequences for self and others, whereas in adulthood the experiences of best friends may be represented similarly to one's own encounters (Fareri, Niznikiewicz, Lee, & Delgado, 2012; Varnum, Shi, Chen, Qiu, & Han, 2014).

Intriguingly, when outcomes for friend and self were tested against fixation baseline, different developmental patterns for TPJ, precuneus and ventral mPFC were revealed. These

analyses allowed us to test specific age-related changes for processing outcomes for friends. In the precuneus neural activation for both self and friend decreased during adolescence, with a stronger decrease for friend compared to self. In a study by Saxbe et al. (2015) participants viewed short video clips of parents and unknown peers, and there was more precuneus activation during peer videos. The precuneus activation in this study was interpreted to reflect the social reorientation of adolescents when peers become more important. The decrease found in precuneus activation over age in this study would fit with this interpretation.

In the left TPJ, activation for friend remained stable across age, whereas activation for self increased with age. The age-related decrease for TPJ for Friend>Self seems inconsistent with prior research, which generally shows an increase in TPJ activity with increasing age (for a meta-analysis, see Crone & Dahl, 2012). However, the post hoc analysis demonstrated that the results are consistent with these prior findings, and the increase is observed specifically for the self-condition. It is possible that participants engaged in perspective taking when processing outcomes for friends, a function purportedly regulated by TPJ (Carter & Huettel, 2013; Mars et al., 2012), which may explain the absence of age differences in the friend condition. The age-related increase in TPJ activity in the self condition may indicate that during adolescence, participants engage in thinking about others when processing outcomes for self. Although this is a new hypothesis that should be tested further in future studies, similar findings were previously reported in a Trust Game. In this study, when participants received trust from another player (a self-relevant outcome), TPJ was more active for adults compared to adolescents, and the extent of activation increased across adolescence (van den Bos, van Dijk, Westenberg, Rombouts, & Crone, 2011). In another study adolescent and adult participants judged social and basic emotions. The results of this study show that in adolescents judgments about social emotions elicits activation in the TPJ

for both self and others, in adulthood however judgment of social emotions results in activation for self and deactivation for others (Burnett et al., 2009).

Finally, there were no age related changes in the ventral mPFC for Friend > Self, nor were there any effects for contrasts testing the separate Friend and Self conditions relative to fixation baseline. These patterns are different from results previously reported in a longitudinal study by Pfeifer et al. (2013). In this study, participants were tested in a self-other attributes task at ages 10 and 13 years old. This longitudinal design showed an increase in ventral mPFC for Self>Friend. The current study did not find age related changes in the ventral mPFC cluster, but one possibility is that this is because we focused on a more ventral region related specifically to Friend (see supplementary material for quadratic age effects in the more dorsal self-related mPFC, consistent with Pfeifer et al, 2013).

Relation with self-report measures

Changes in neural activation are difficult to interpret per se, i.e. when they are not related to a specific type of behavioral change. To better understand these changes, we tested the relation between self-report measures and neural activation, and the longitudinal design provided an excellent opportunity to test these brain-behavior relations. For this purpose, we assessed friend relationship information i.e. friendship quality, and self-report ratings of how much participants felt that their friend deserved to win.

Firstly, friendship quality was related to the self-report rating of how much their friend deserved to win. However, friendship quality was not related to age or neural activation in any of the regions of interest. In this study, all participants played for their best friend, and friendship quality was relatively high for all participants. Possibly, there are relations with friendship quality and neural responses in social brain in a sample with more variability in friendship quality.

Secondly, how much participants felt that their friend deserved to win was positively related to neural activation in the ventral mPFC and precuneus. A study by Aue (2014) found more precuneus activation when a desirable outcome was predicted compared to when an undesirable outcome was predicted. If participants think that their friend deserves to win more, this might reflect a more desirable outcome and could subsequently explain the observed differences in precuneus activation. This explanation is strengthened by the observed relation between friendship quality and how much participants felt their friend deserved to win. This relation was in the expected direction: participants who reported higher friendship quality also reported that they felt their friend deserved to win more. However, the precuneus is a neural region associated with many functions (Cavanna & Trimble, 2006). For example it has been suggested that the precuneus might reflect self-related thoughts. A study investigating vicarious embarrassment found that participants who reported higher social closeness with their friends also showed higher precuneus activation when they saw their friends' social integrity being threatened (Müller-Pinzler, Rademacher, Paulus, & Krach, 2015). Based on these results one alternative explanation for the relation between precuneus activation and the self-report rating could be that those participants who felt that their friend deserved to win more, also experience more overlap with their friends. However, this hypothesis should be tested in more detail in future studies.

Limitations and future directions

A limitation of the current paradigm is that we did not include a formal, non-social baseline condition. A suitable baseline condition for future studies could include receiving outcomes for a computer (Delgado, Frank, & Phelps, 2005). To describe the developmental trajectories in more detail, we tested patterns of change against a fixation baseline. Our analyses revealed important information about developmental changes within our self and

friend conditions, however a nonsocial baseline condition (e.g. outcome for computer) could provide a more specific social vs. nonsocial comparison. Future studies should test whether the developmental patterns observed in the current study are also observed when tested against a non-social baseline condition.

It is also important to note that there was high variability in the extent to which neural regions were recruited in this study. That is to say, test-retest stability was considered low especially in the ventral mPFC, and this stands in sharp contrast with studies using cognitive control paradigms which have reported fair to good test-retest across periods of months (Bennett & Miller, 2013) and years (Koolschijn, Schel, de Rooij, Rombouts, & Crone, 2011). To our knowledge, this is the first study reporting test-retest stability in a longitudinal study on social brain regions. Future studies should test the reliability and stability of social brain activity across shorter time intervals (i.e. days or weeks) to assess how variable these activities are over time.

Furthermore, future studies could focus on the role of changing friendships in adolescence. As friendships and best friends change often during adolescence (Bowker, 2004), future work could test whether social processing is more related to friendship duration or friendship quality. In the current sample not all participants reported having the same friend two years later. Even though we did not find any differences in friendship quality measures for participants who did and did not report the same friend at both time points, future experiments could measure adolescent friendship quality more frequently to better capture the changing nature of their social environment. The current paradigm is a relatively simple task that measures more automatic processing of social information, which differs from many commonly used social paradigms that capture more deliberate processes. As such, future studies could benefit from comparing automatic and deliberate social processing.

Conclusion

Taken together, the current results confirm continuous changes in the social brain network across age during the processing of feedback for the self and a close other. Further, these findings demonstrate that social relationships are related to these changes in social brain recruitment. The rating for how much a friend deserved to win showed a positive linear relation with activation in ventral mPFC and the precuneus. This means that participants who most strongly believed that their friend deserved to win showed the highest activation in these regions when playing for a friend vs. playing for themselves.

Future studies should test how these patterns are related to daily life experiences of adolescents by using multiple sampling procedures. The current findings provide evidence to elucidate the relation between brain change and behavioral change and reveal the developmental dynamics of the social brain. Future longitudinal studies will further reveal how neural development is influenced by positive and negative social experiences, such as having positive peer relations (Will, van Lier, Crone, & Guroglu, 2015), or experiencing positive parental affect (Tan et al., 2014).

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Figure legends

Figure 1. Example of a trial. On trial onset, participants were presented with a screen for 4000 ms indicating how many coins could be won or lost. During this time, participants chose to play heads or tails by pressing the corresponding button. After a 1000 ms delay, trial outcome was presented for 1500 ms. Participants won when the computer randomly selected the same side of the coin as chosen by the participant, see also (Braams et al., 2013).

Figure 2. Graphic display of the regions of interest used to extract parameter estimates. Displayed are the right TPJ (MNI 55 -54 27), precuneus (MNI 2 -58 46) and a ventral medial prefrontal cortex cluster (MNI 1 57 12). Not displayed the left TPJ (MNI -55 -54 27).

Figure 3. A) The predicted values for the best fitting model for each region of interest. Shaded areas represent 95% confidence interval. B) Predicted values for the best fitting model for Friend > Fixation and Self > Fixation for each region of interest. Shaded areas represent 95% confidence interval.

Table 1. Intra Class Correlations for contrast values of the contrast Friend > Self for all regions of interest.

Region of Interest	ICC
Ventral mPFC	.054
Precuneus	.127
TPJ Left	.159
TPJ Right	.356

Table 2. AIC and BIC values for null, linear and quadratic models. Preferred models, based on AIC values, BIC values and a log likelihood ratio test, are highlighted in bold.

	Model					
	Null		Linear		Quadratic	
	AIC	BIC	AIC	BIC	AIC	BIC
Precuneus						
Friend > Self	2553	2566	**2551**	**2567**	2550	2570
Friend > Fix	2811	2824	**2798**	**2814**	2799	2820
Self > Fix	2672	2685	**2667**	**2684**	2669	2689
TPJ L						
Friend > Self	2183	2195	**2178**	**2195**	2180	2200
Friend > Fix	**2264**	**2276**	2266	2282	2268	2289
Self > Fix	2136	2149	**2133**	**2150**	2135	2156
TPJ R						
Friend > Self	2179	2191	**2175**	**2192**	2175	2196
Friend > Fix	**2302**	**2314**	2304	2321	2305	2326
Self > Fix	**2234**	**2246**	2232	2249	2234	2255
Ventral mPFC						
Friend > Self	**2644**	**2656**	2644	2661	2646	2667
Friend > Fix	**2668**	**2680**	2667	2683	2666	2687
Self > Fix	**2676**	**2689**	2678	2695	2678	2699

Table 3. Variances, beta's, *p* values and 95% confidence intervals (CI) for best fitting models for the relation between age and neural activation in the regions of interest. Linear age terms are represented by Age[1].

		variance	*β*	*p* value	95% CI	
					lower	upper
Precuneus						
Friend > Self						
Random effect	Intercept	0.76			.207	2.84
Fixed effects	Intercept		1.39	<.001	1.09	1.70
	Age[1]		-7.40	.031	-14.1	-.682
Friend > Fix						
Random effect	Intercept	2.58			2.11	3.20
Fixed effects	Intercept		1.81	<.001	1.36	2.25
	Age[1]		-19.4	<.001	-28.9	-9.90
Self > Fix						
Random effect	Intercept					
Fixed effects	Intercept					
	Age[1]					
TPJ L						
Friend > Self						
Random effect	Intercept	.638			.263	1.54
Fixed effects	Intercept		.757	<.001	.547	-1.59
	Age[1]		-6.20	.009	-10.8	-1.59
Friend > Fix						
Random effect	Intercept	1.47			1.19	1.81
Fixed effects	Intercept		.908	<.001	.652	1.17
Self > Fix						
Random effect	Intercept	1.08			.812	1.43
Fixed effects	Intercept		.157	.153	-.058	.372
	Age[1]		5.18	.029	.545	9.82
TPJ R						
Friend > Self						
Random effect	Intercept	1.06			.811	1.39
Fixed effects	Intercept		.747	<.001	.525	.969
	Age[1]		-5.86	.017	-10.7	-1.05
Friend > Fix						
Random effect	Intercept	1.68			1.41	2.02
Fixed effects	Intercept		1.25	<.001	.971	1.52
Self > Fix						

Random effect	Intercept	1.57			1.31	1.89
Fixed effects	Intercept		.491	<.001	.023	.748
Ventral mPFC						
Friend > Self						
Random effect	Intercept	.556			.000	931.1
Fixed effects	Intercept		.608	<.001	.274	.941
Friend > Fix						
Random effect	Intercept	1.95			1.48	2.58
Fixed effects	Intercept		.747	<.001	.370	1.13
Self > Fix						
Random effect	Intercept	1.42			.828	2.42
Fixed effects	Intercept		.135	.462	-.226	.497

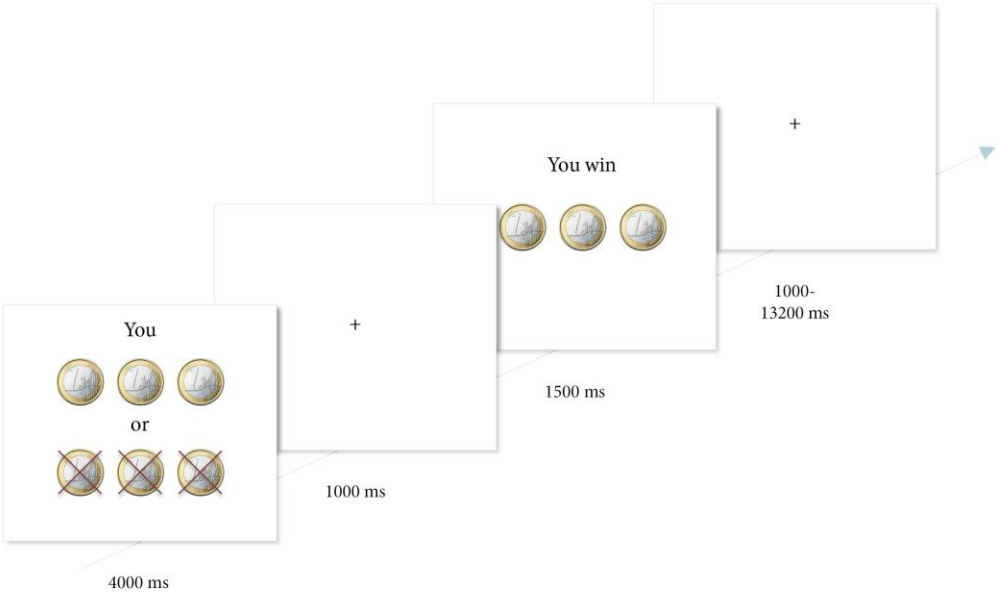

Figure 1. Example of a trial. On trial onset, participants were presented with a screen for 4,000 ms indicating how many coins could be won or lost. During this time, participants chose to play heads or tails by pressing the corresponding button. After a 1,000-ms delay, trial outcome was presented for 1,500 ms. Participants won when the computer randomly selected the same side of the coin as chosen by the participant (see also Braams et al., 2013).

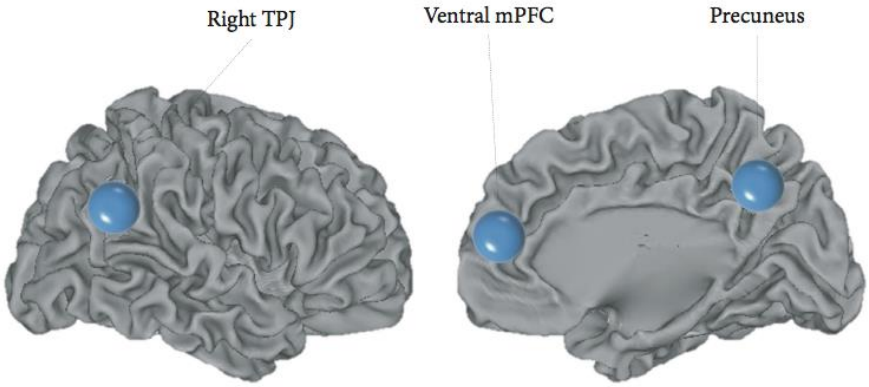

Figure 2. Graphic display of the regions of interest used to extract parameter estimates. Displayed are the right temporoparietal junction (TPJ; MNI 55 −54 27), precuneus (MNI 2 −58 46), and a ventral medial prefrontal cortex cluster (MNI 1 57 12). Not displayed the left TPJ (MNI −55 −54 27). [Color figure can be viewed at wileyonlinelibrary.com].

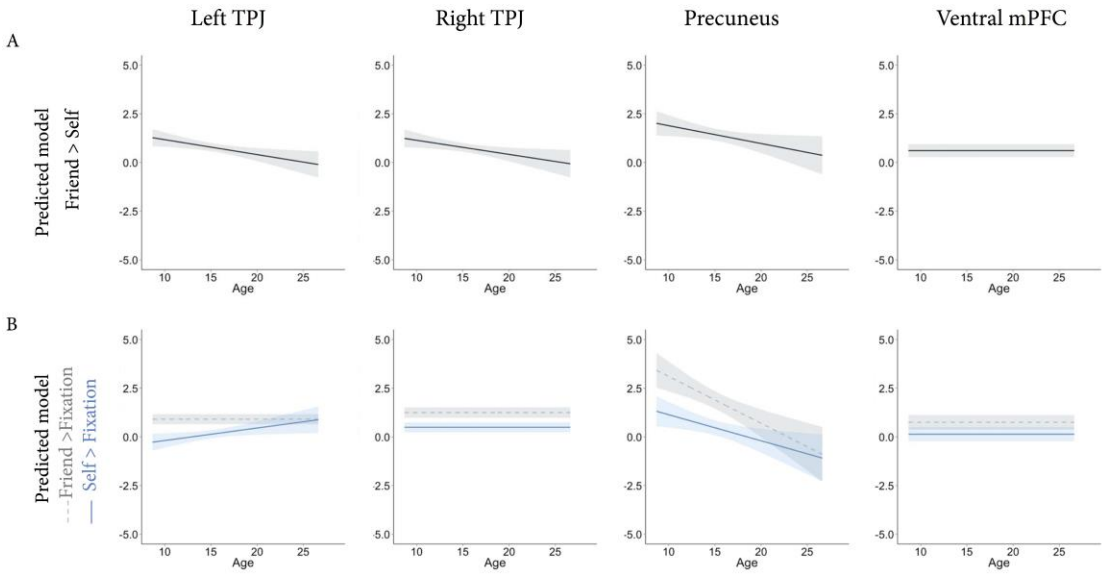

Figure 3. (A) The predicted values for the best-fitting model for each region of interest (ROI). Shaded areas represent 95% CI. (B) Pre- dicted values for the best-fitting model for friend > fixation and self > fixation for each ROI. Shaded areas represent 95% CI.