Helping me, helping you: behavioral and neural development of social competence from childhood to adolescence

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CHAPTER 5

Transitions in social responsivity from childhood to adolescence: developmental patterns, neural correlates and associations with wellbeing

This chapter is submitted for publication as:
Dobbelaar, S., van Drunen, L., van Duijvenvoorde, A.C.K., van IJzendoorn, M.H., Crone, E.A., & Achterberg, M. (submitted). *Transitions in social responsivity from childhood to adolescence: developmental patterns, neural correlates and associations with wellbeing.*

ABSTRACT

The transition between middle childhood and early adolescence is an important period in the development of adaptive responses to the social context, specifically to social rejection of self and others. Aggression in response to rejection of self and prosocial behavior in response to observed rejection of others can co-occur and both behaviors may indicate social responsivity. This study examined the developmental patterns and neural correlates of social responsivity in a 3-wave behavioral-fMRI study (ages 7-13 years, T1: n=512, 51% girls; 91% middle to high SES; T3: n=456, T5: n=336). Moreover, we examined the association between social responsivity and future wellbeing, using a fourth behavioral follow-up assessment (T6: n=294). Aggression following rejection was measured using the Social Network Aggression Task and prosocial behavior following observed exclusion was measured using the Prosocial Cyberball Game. We defined social responsivity subgroups based on the co-occurrence of aggression and prosocial behavior. Results revealed instability of subgroups over time. Neural comparisons showed that social responsivity was associated with increased mPFC activation during observed exclusion and decreased mPFC activation during self-related rejection, suggesting increased neural sensitivity to other-focused processes in socially responsive children. Subgroup analyses revealed different brain-behavior patterns in middle childhood and early adolescence, suggesting transitions in mPFC sensitivity. Finally, social responsivity in early adolescence was predictive of personal wellbeing one year later. These findings contribute to our understanding of why some children may be more responsive to social rejection than others and how this responsivity may hinder or promote developmental outcomes later in adolescence.

Keywords: social rejection, reactive aggression, prosocial behavior, fMRI, wellbeing, development

INTRODUCTION

The ability to flexibly read, understand and adapt to social situations is an important prerequisite for developing and maintaining social relations (Crone et al., 2020). The period between childhood and adolescence is marked by increased social interactions and experiences (Blakemore & Mills, 2014; Crone et al., 2020; Lam et al., 2014), and is therefore a key period for the development of these adaptive social behaviors. Two key components of social behavior are regulating reactive aggression following social rejection (Achterberg et al., 2016) and prosocial helping behavior following observed rejection of others (Van der Meulen et al., 2016). Although these behaviors are often studied as two separate and mostly opposite constructs (Card & Little, 2006), aggression and prosocial behavior can also co-occur (e.g., Boxer et al., 2004; Dobbelaar et al., 2021; Ettekal & Mohammadi, 2020). As reactive aggression is often displayed in response to rejection of oneself and prosocial behavior in response to observed rejection of others, both may indicate a certain responsivity to social contexts (Crone et al., 2020; Hawley, 2002). This study focuses on the development and neural mechanisms of social responsivity (i.e., reactive aggression and prosocial behavior) and associations with wellbeing in the important transition period between childhood and adolescence (7-13 years).

Development of social responsivity

Developmental patterns of reactive aggression and prosocial behavior are often studied separately. Generally, reactive aggression, i.e., the defensive response to frustration or provocation (Crick & Dodge, 1996), decreases between late childhood and adolescence (Cui et al., 2016; Fite et al., 2008), although studies also report a peak in reactive aggression for some individuals in adolescence (Barker et al., 2006; Lickley & Sebastian, 2018). Findings on the development of prosocial behavior are mixed, with some studies reporting decreases in teacher-reported prosocial behavior (Kokko et al., 2006; Malti et al., 2015) and others reporting increases in early adolescence (Padilla-Walker et al., 2018; van der Meulen et al., under review; Westhoff et al., 2021; Zondervan-Zwijnenburg et al., 2022). Studying how these key components of social responsivity co-occur from childhood to adolescence might help us to better understand the development and stability of social responsivity in this important developmental period, during which children transition from a close circle of friends to a more extended social world. Previously, we proposed a bi-dimensional model to study the co-occurrence of behavioral responses to rejection of self and others (Crone et al., 2020). In this model, four subgroups were characterized along the dimensions of reactive aggression (in response to rejection of the self) and prosocial behavior (in response to observed rejection of others; see Figure 1). Prior work in 7–9-year-olds indeed showed variation in the co-occurrence of reactive aggression and prosocial behavior, supporting the existence of subgroups that differ in behavioral social responsivity in middle childhood (Dobbelaar et al., 2021). Similar subgroups of individuals who use both prosocial and aggressive strategies were also found in adolescence (Boxer et al., 2004; Hartl et al., 2020). However, it is unclear whether these subgroups of social responsivity remain stable across childhood and adolescence. Research on personality traits has shown both stability and change across childhood and adolescence, with stability increasing across time (Shiner, 2015). The first aim of this study was therefore to explore stability of social responsivity subgroups, based on the bidimensional model of Crone et al. (2020), from childhood to early adolescence.

Neural correlates of social responsivity

Differences in the behavioral subgroups of social responsivity may possibly be explained by differences in neural sensitivity to social feedback to self and others. Neuroscience studies may be a promising method for understanding underlying neural sensitivity to various forms of social adaptive behavior. Prior studies point towards the mPFC as important region in self- and other-oriented processes, such as in social and affective processing and social cognition (Blakemore & Mills, 2014; Crone et al., 2020; Crone & Fuligni, 2020; Yoon et al., 2018). The specific role of the mPFC in self-oriented processes can be studied using functional magnetic resonance imaging (fMRI) in combination with experimental tasks, for example using the Social Network Aggression Task (SNAT; Achterberg et al., 2016). Using this approach, studies showed increased activation in the mPFC during rejection feedback compared to acceptance feedback, in both adults and children (Achterberg et al., 2016, 2018; Davis et al., 2022; Dobbelaar, Achterberg, van Drunen, et al., 2022; Wikman et al., 2022). However, this is not consistently reported by other studies (Gunther Moor et al., 2010; Guyer et al., 2012), which may be explained by the finding that the mPFC has also been implicated in processing socially salient events, i.e., during both rejection and acceptance feedback compared to neutral feedback (Achterberg et al., 2016; Davis et al., 2022; Dobbelaar, Achterberg, van Drunen, et al., 2022; Wikman et al., 2022).

Effects of both rejection of oneself and of observed rejection of others can be studied using the Prosocial Cyberball Game (PCG; Riem et al., 2013; van der Meulen et al., 2016). In this task, participants played a four-player ball-tossing game where participants observe that one player is excluded by the other two players. Studies using the PCG and related tasks showed increased mPFC activation both when experiencing exclusion (vs. inclusion) as well as when observing exclusion of others (Masten et al., 2011; Tousignant et al., 2018; van der Meulen et al., 2016, 2018). Interestingly, mPFC activation during rejection in the SNAT and experienced exclusion in the PCG was correlated (Crone et al., 2020), emphasizing the important role of the mPFC in the neural processing of rejection feedback. To understand whether increased mPFC sensitivity underlies social responsivity in childhood and adolescence, the second aim of this study was to examine whether subgroups of social responsivity differed in neural sensitivity (i.e., mPFC activation) during social rejection of self and others.

Social responsivity as precursor of wellbeing

In prior studies, the co-occurrence of aggression and prosocial behavior have been linked to developmental outcomes. That is, the combination of reactive aggression and prosocial behavior in middle childhood has been linked to lower externalizing problems one year later (Dobbelaar et al., 2021), suggesting that social responsivity may be a protective factor against risk for behavioral problems in childhood. However, whether it is also a promotive factor for wellbeing later in adolescence, a crucial period for social and emotional development (Blakemore & Mills, 2014), remains to be studied. Wellbeing is defined as someone's appraisal and evaluation of their life (Diener, 2009) and is often viewed as a multi-faceted construct including feelings about life satisfaction, purpose, relationships, self-confidence and feeling appreciated (Diener & Ryan, 2009; Green, van de Groep, et al., 2023).

As social responsivity can indicate adaptation to different social contexts, it may help in building social relations and thereby promote wellbeing. Both aggression and prosocial behavior can be used as strategies to achieve social goals (Hawley, 1999) and adolescents who were both aggressive and prosocial were found to be socially skilled and liked by peers (Hartl et al., 2020; Hawley, 2003, 2014). Furthermore, both self-protective aggression and prosocial behavior may aid in maintaining positive self-views (Crocetti et al., 2016; Crone & Fuligni, 2020; Rodman et al., 2017). Alternatively, higher social responsivity could also be related to lower wellbeing in adolescence, as individuals who are behaviorally more responsive to social rejection may be more sensitive to social cues in general, which has been linked to adjustment problems (Chen et al., 2018; Sobocko & Zelenski, 2015). To disentangle these two possibilities, the third and final aim of this study was to test whether social responsivity was predictive of wellbeing in adolescence.

Current study

Corresponding to the three aims of the current study, we examined 1) stability of subgroups of social responsivity, 2) neural mechanisms underlying social responsivity (i.e., mPFC sensitivity to social rejection), and 3) social responsivity as precursor for later wellbeing. Using the bi-dimensional model of Crone et al. (2020), we defined social responsivity subgroups in the longitudinal twin study of the Leiden Consortium on Individual Development (L-CID). Ultimately, understanding individual differences, mechanisms and developmental outcomes of social responsivity may contribute to answering the important question why some children have more difficulties in developing social relations than others, and how children may best be supported to thrive.

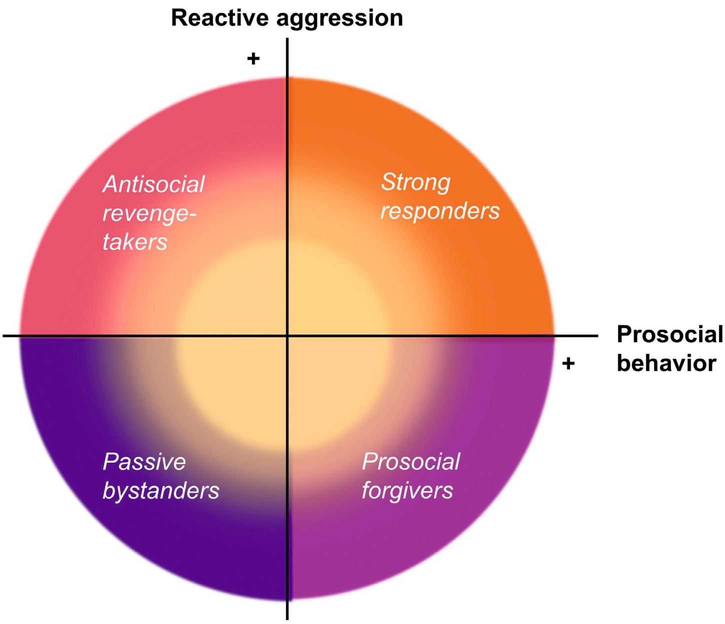

Figure 1. Bi-dimensional model of social responsivity as proposed by Crone et al. (2020), combining prosocial behavior and reactive aggression into four subgroups.

METHODS

Participants

This study focused on the middle childhood cohort of the cohort-sequential longitudinal twin study the Leiden Consortium on Individual Development (L-CID; Crone et al., 2020; Euser et al., 2016). In total, 514 children participated in the middle childhood cohort (ages 7-15 years, 51.4% girls, 48.6% boys). The data included in the present study focused on the three biannual MRI waves at the first timepoint (T1; n=512, mean age=7.95±0.67 years, age range = 7.02-9.68 years, 51.2% girls, 48.8% boys), third time point (T3; n=456, mean age=9.98±0.69 years, age range = 8.97-11.67 years, 52.2% girls, 47.8% boys) and fifth time point (T5; n=336; mean age=12.41±0.76

years, age range = 11.15-14.11 years, 52.4% girls, 47.8% boys), and on the online questionnaire at the sixth time point of data collection (T6; n=294; 12-15 years, mean age=13.35±0.80 years, age range = 11.98-15.10 years, 54.1% girls, 45.9% boys). Demographic characteristics of the total sample at each time point are presented in Table 1. Demographic characteristics and exclusion criteria of specific measures (behavioral, fMRI and questionnaires) are presented in Figure 2.

Invitations were sent to families of same-sex twins born between 2006 and 2009, who lived in the western municipalities of the Netherlands. Participants were included when they were fluent in Dutch or English, had normal or corrected to normal eye vision and did not have physical impairments that could hinder their task performance. The study was approved by the Dutch Central Committee on Research Involving Human Subjects (CCMO; number NL50277.058.14). Written informed consent was obtained from both parents at the start of the study, and from children once they turned 12.

Table 1. Demographic characteristics of the complete samples at T1, T3, T5 and T6.

	T1	T3	T5	T6
N	512	456	336	294
Age (SD) in years	7.95 (0.67)	9.98 (0.69)	12.41 (0.76)	13.35 (0.80)
Age range	7.02 – 9.68	8.97 – 11.67	11.15 – 14.11	11.98 – 15.10
Sex at birth (% girls/boys)	51.2 / 48.8	52.2 / 47.8	52.4 / 47.6	54.1 / 45.9
SES*: low-middle high (%)	8.6 – 45.7 – 45.3	6.6 – 46.1 – 46.9	3.6 – 46.4 – 49.4	3.4 – 45.9 – 50.7
Psychiatric diagnosis (n)	11	16	19	- ***
- ADHD/ADD	9	9	9	-
- ADHD/ADD & DCD	0	1	1	-
- ASD	1	3	4	-
- GAD	1	2	2	-
- other	0	1	3	-
Mean IQ** (SD)	103.58 (11.76)	103.81 (11.63)	104.29 (11.89)	104.25 (11.95)
IQ range	72.50 – 137.50	72.50 – 137.50	72.50 – 137.50	72.50 – 137.50
Monozygotic (%)	54.7	54.4	56.0	58.2
Country of birth parents (%)				
- both parents born in the Netherlands	93.7	94.2	94.0	94.5
- one parent born in the Netherlands	5.5	5.4	5.4	4.8
- both parents born outside of the Netherlands	0.8	0.4	0.6	0.7
Data collection period	2015 – 2016	2017 – 2018	2019 – 2021	2021

Note. * Socio economic status (SES), based on parental education at T1. SES data of 1 family (2 participants) is missing. ** Intelligence quotient, based on the WISC (3rd edition) subtests "similarities" and "block design" at T1. *** At T6, no information on psychiatric diagnoses was collected. Abbreviations: ADHD/ADD = attention deficit (hyperactivity) disorder, DCD = developmental coordination disorder, ASD = autism spectrum disorder, GAD = generalized anxiety disorder.

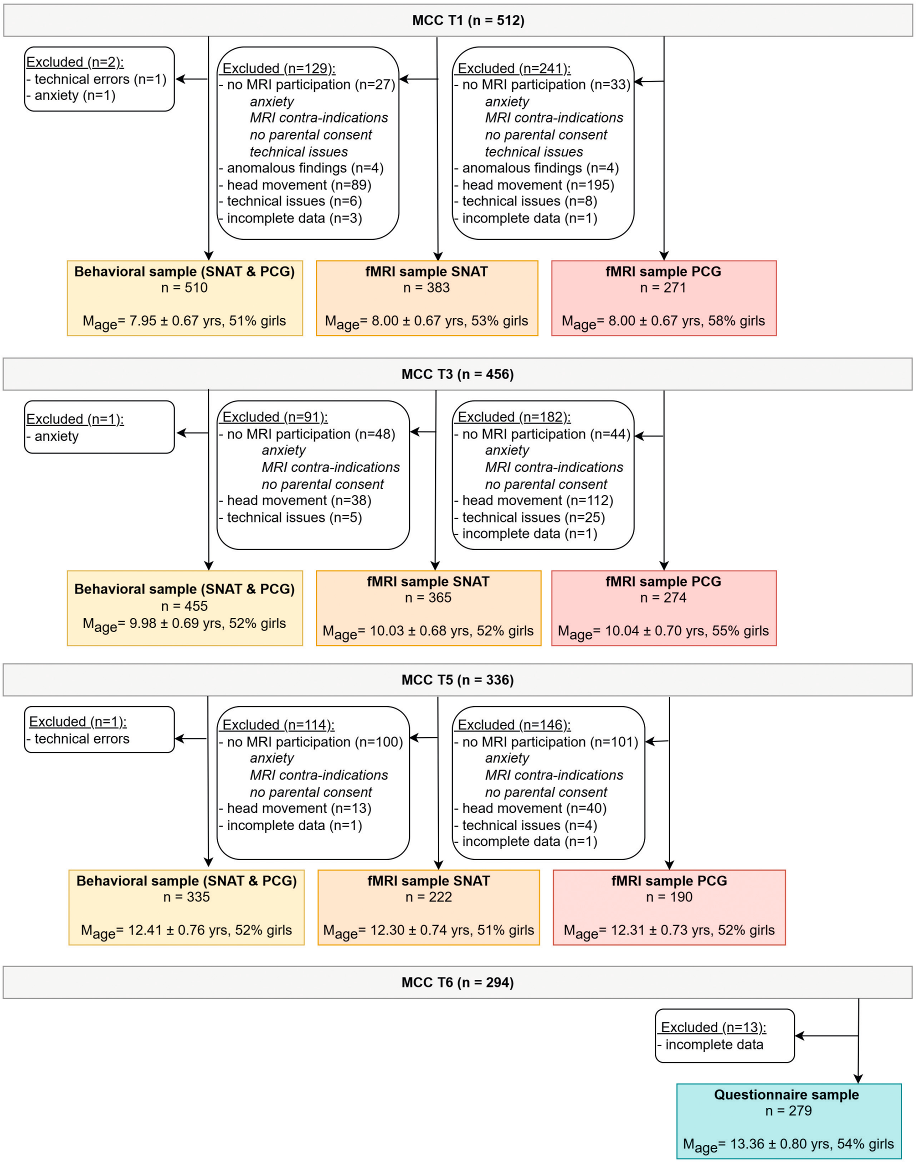

Figure 2. Flowchart of inclusion of participants for the behavioral measures, fMRI measures and questionnaire data.

Procedure

Data were collected during annual visits with alternating lab (MRI) and home visits. Lab visits took place at the Leiden University Medical Center, where participants participated in an MRI session, performed behavioral tasks and filled out questionnaires. The order of task administration was counterbalanced, such that one of the twins first participated in the MRI session, while the other first performed the behavioral tasks. Both parents filled out questionnaires prior to or during the lab visit. At T6, families participated in an online home visit, where they performed behavioral tasks online and filled out questionnaires using Qualtrics.

Behavioral measures

Social Network Aggression Task

To measure reactive aggression, we used the Social Network Aggression Task (SNAT), which was previously validated as measure of aggression following social feedback in children and adults (Achterberg et al., 2016, 2017). In this task, participants received peer feedback on a personal profile that they filled out prior to each lab visit. During the lab visit, participants were told that other peers had read their profile and had provided feedback on whether they liked their answers (positive feedback, displayed as a green thumb up), disliked their answers (negative feedback, displayed as a red thumb down), or neither liked nor disliked their answers (neutral feedback, displayed as a grey circle).

During the task, participants were presented with this peer feedback and were instructed to subsequently send a noise blast to the peer who provided the feedback. They sent the noise blast by pressing a button with their right index finger. Participants were instructed to always send a noise blast but could decide the duration of the blast themselves. The longer they pressed the button, the more the volume and duration of the noise blast would increase, which was used as measure of aggression. The duration of the noise blast was displayed in a volume bar, where each 350ms a new colored box would appear (Figure 3a). To inform participants about the volume of the noise blast, participants heard the volume of the noise blast twice during the practice task: once with increasing volume and once with maximum volume. Next, participants practiced six trials (two negative feedback, two neutral feedback and two positive feedback trials).

The SNAT consisted of sixty trials, that were presented in three blocks of twenty trials. Twenty trials were presented for each feedback condition, and the order of these trials was pseudorandomized, such that no more than three trials of the same feedback condition were presented in a row. A trial consisted of a fixation screen of 500ms, the social feedback screen for 2500ms, a jittered fixation screen for 3000-5000ms, the noise screen for 5000ms and an intra-trial fixation screen for 0-11550ms (Figure 3a). To send a noise blast, participants had to press the button as fast as possible when the noise screen appeared. Each 350ms, a new colored box would appear that indicated an increase in volume of the noise blast. When participants released the button or after 3500, the volume bar was presented for the remaining 5000ms. When participants did not press the button within 1500ms, a screen would appear with the message "too late!" for the remaining 3500ms. These trials were regarded as invalid and were not included in the analyses.

Reactive aggression was operationalized as the difference score between noise blast duration following negative feedback and noise blast duration following neutral feedback.

Prosocial Cyberball Game

To measure prosocial behavior, we used the Prosocial Cyberball Game (PCG), which was previously validated as measure of prosocial compensating behavior in children and adults (Riem et al., 2013; van der Meulen et al., 2016, 2017). In this task, participants played a computerized ball-tossing game with three other pre-programmed players presented on the screen (Figure 3b). In the first block (120 trials), the Fair block, each participant received the ball equally (25% of the tosses to each player). In the second and third block (84 trials per block), the Unfair blocks, player 1 and 3 (the "excluders", displayed at the left and right of the screen) no longer tossed the ball to player 2 (the "excluded player", displayed at the top of the screen). Player 2 still tossed the ball to all players equally. When the participant received the ball from one of the other players, participants were instructed to toss the ball to another player by pressing a button with their right index, middle or ring finger (for player 1, 2 or 3, respectively).

A trial consisted of a ball toss for 2000 ms and an intra-trial interval for 1000-2000 ms. For trials where participants tossed the ball, the intra-trial interval consisted of the response time of the participant. At T1, participants performed the Fair block on a laptop outside the MRI scanner and the Unfair blocks in the MRI scanner. At T2 and T3, all blocks were performed in the MRI scanner. For our MRI analyses, we focus only on neural activation during the Unfair blocks, where player 2 was excluded.

Prosocial compensating behavior was operationalized as the difference score between the percentage of tosses to player 2 in the Unfair blocks and the percentage of tosses to player 2 in the Fair block.

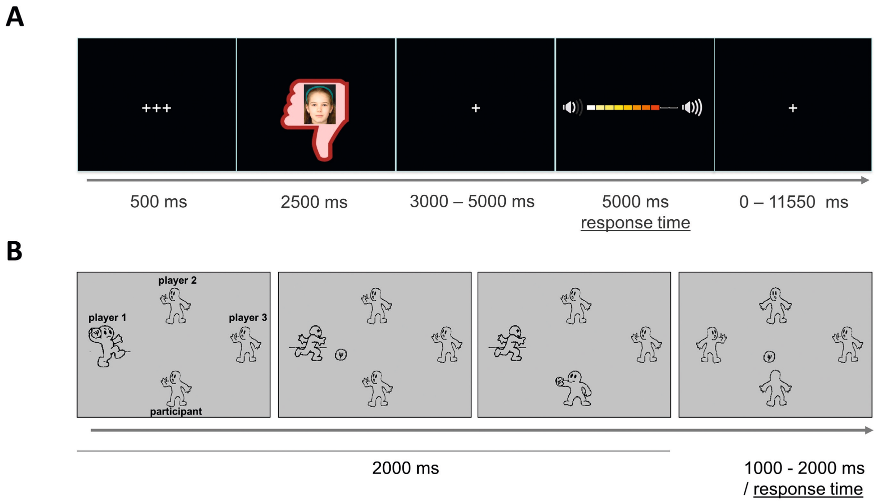

Figure 3. Schematic representation of a trial in A) the Social Network Aggression Task, and B) the Prosocial Cyberball Game.

Wellbeing Questionnaire

To measure wellbeing at T6, we used a self-reported Wellbeing Questionnaire, which we developed a-priori based on of 35 items of validated questionnaires. We used 10 items from the Multidimensional Wellbeing in Youth Scale (MWYS; Green et al., 2023), 10 items from the World Health Organization Quality of Life Scale (WHOQoL; Vahedi, 2010) and 15 items from the Harter's Self-Perception Profile for Adolescents (SPPA; Harter, 1988; Wichstraum, 1995). From the SPPA, we specifically used the three subscales Global Self-worth (GS), Social Competence (SC) and Close Friendships (CF), where each subscale consisted of five items. All items were answered on a four-point scale, ranging from 0 - 3. The subscales included items such as '*Do you feel confident?*' (MWYS), '*How much do you enjoy life?*' (WHOQoL) and '*some teenagers find it hard to make friends, but other teenagers find it pretty easy to make friends*' (SPPA – SC). Higher scores indicate higher wellbeing. Items and response options of the complete questionnaire are presented in the supplementary materials.

We performed a principal component analysis (PCA) with Varimax rotation to factor analyze the 35 items of the questionnaire. The items were suitable for the PCA, as indicated by the KMO measure (.915) and Bartlett's test of sphericity ($\chi^2(595) = 4387.87$, $p<.001$). The analysis resulted in two factors, explaining 25.85% and 12.83% of the variance, respectively. The rotated component matrix revealed that the first factor ('Personal Wellbeing') included loadings above 0.4 on 24 items, from the MWYS, WHOQoL and SPPA – Global Self-worth subscales. The second factor

('Social Wellbeing') included loadings above 0.4 on 11 items, from the SPPA – Social Competence, SPPA – Close Friendships and one item from the MWYS (i.e., '*Do you feel like you can talk to your friends about what's bothering you?*'). Two items (MWYS: '*Do you feel like you can talk to your friends about what's bothering you?*' and SPPA-GS: '*Some teenagers are very happy being the way they are but other teenagers often wish they were different*') loaded on both factors and were included in the factor with the highest loading.

We created the two subscales (Personal Wellbeing and Social Wellbeing) by averaging the 24 and 11 items, respectively. Higher scores indicated higher wellbeing. Both subscales showed good reliability (Personal Wellbeing: *Cronbach's* $\alpha = 0.93$; Social Wellbeing: *Cronbach's* $\alpha = 0.80$). On average, participants had a mean score of 2.28 ± 0.41 for personal wellbeing and of 2.29 ± 0.49 for social wellbeing. The two subscales of wellbeing were positively correlated ($r = 0.53$, $p < .001$). Moreover, the personal wellbeing subscale was significantly associated with age ($F(1,143.11) = 4.42$, $p = .021$), such that older adolescents reported lower personal wellbeing ($r = -0.17$). Furthermore, we found sex differences ($F(1,144.06) = 4.81$, $p = .030$), with boys ($M = 2.34$, $SD = 0.37$) reporting higher personal wellbeing than girls ($M = 2.15$, $SD = 0.44$). Boys and girls did not differ in age ($t(314.82) = 0.98$, $p = .329$), excluding the possibility that the sex effects were driven by age differences. On the social wellbeing subscale, we did not find age or sex effects (all $p \geq .187$).

Neuroimaging measures

fMRI data acquisition

For the three waves of MRI data collection, scans were acquired on the same Philips Ingenia 3.0 Tesla MR scanner, using a standard whole-head coil. Foam inserts were placed within the head coil to minimize head movement. Stimuli were presented on a screen placed behind the scanner that participants could view through a mirror on the head coil. fMRI scans were collected using T2*-weighted echo planar imaging (EPI). The first two volumes were discarded to allow for equilibration of T1 saturation effects (Field of View (FOV)=220x220x111.65 mm; TR=2.2 s, TE=30 ms, FA=80°; sequential acquisition; 37 slices; voxel size=2.75x2.75x2.75 mm). In addition, a high-resolution 3D T1 scan was collected as anatomical reference (FOV=224x177x168 mm; TR=9.72 ms; TE=4.95 ms; FA=8°; 140 slices; voxel size=0.875x0.875x0.875 mm).

fMRI preprocessing

fMRI data were analyzed in SPM12 (Wellcome Department of Cognitive Neurology, London). Preprocessing steps included a correction for slice timing acquisition and rigid body motion, spatial normalizing to T1 templates (based on MNI-305 stereotaxic space; Cocosco et al., 1997) using 12-parameter affine transform mapping and non-linear transformation with cosine basis functions, resampling to 3x3x3 mm voxels and spatial smoothing using a 6mm full-width-at-half-maximum isotropic Gaussian kernel. For both the SNAT (consisting of three blocks) and PCG (consisting of two Unfair blocks), data of participants with at least two blocks of fMRI data with <3 mm movement in every direction were included in the first-level analyses at that time point (see Figure 2 for excluded number of participants for each measure).

fMRI first-level analyses

fMRI data of individual participants at each time point were analyzed using a general linear model. Six motion regressors were included as covariates of no interest. The least-squares parameter estimates (PE) of height of the best fitting canonical hemodynamic response function were used in pairwise contrasts.

In the SNAT, a trial consisted of two events: the feedback event and the noise blast event. For the feedback event, feedback delivery was modeled as zero-duration event with the valence of the feedback as separate regressors ('Positive', 'Neutral', 'Negative'). For the noise blast event, the start of the noise blast was modeled for the length of the noise blast duration and with valence of the feedback as separate regressors ('PositiveNoise', 'NeutralNoise', "NegativeNoise'). Trials on which participants did not respond were modeled as covariates of no interest and excluded from further analysis. To study neural correlates of social rejection, we focused on neural activation during negative feedback compared to neutral feedback ('Negative' > 'Neutral').

In the PCG, the start of each ball toss was modeled as zero-duration event. We distinguished between three processes which were matched for motor responses: the first contrast examined neural activation associated with experiencing exclusion. This contrast involved ball tosses between the excluders (player 1 and 3) (i.e., exclusion) versus the participant receiving the ball from the excluders (player 1 and 3) (i.e., inclusion). The second contrast examined neural activation associated with observing one player being excluded. This contrast involved ball tosses between the excluders (player 1 and 3) (i.e., exclusion) versus ball tosses by player 2 to the excluders (player 1 and 3) (i.e., connecting).

fMRI region of interest analyses

Our region of interest (ROI) was based on prior work by Crone et al. (2020) in 7-9-year-olds. Specifically, we selected the MPFC region that was activated during both social rejection in the SNAT and experienced exclusion in the PCG (Crone et al., 2020; see Figure 6a). Center of mass coordinates were: x = -2.25, y = 59.1, z = 27.2 (see https://osf.io/unkjd/ for 3D NifTI file of the ROI). Using the MarsBar toolbox (Brett et al., 2002), we extracted parameter estimates for the contrast 'Negative > Neutral' in the SNAT and for the contrasts 'Exclusion > Inclusion' and 'Observed Exclusion > Connecting' in the PCG.

Data analysis

Transparency and openness

Analyses were performed in R (R Core Team, 2013) using the lme4 package for linear mixed models. Results of the linear mixed models were inspected with type III ANOVA's using Satterthwaite's method. Study materials, code and data will be made available upon request in DataverseNL. The study was not preregistered.

Social responsivity scores

Subgroups of social responsivity. First, we divided participants into subgroups of prosocial behavior and reactive aggression according to the bi-dimensional taxonomy of social responsivity (Crone et al., 2020; see Figure 1). To do so, we first calculated the mean scores and standard deviations of reactive aggression (noise blast duration following negative – neutral feedback) and prosocial behavior (% tosses to player 2 in exclusion – inclusion blocks) across participants at each time point. Next, we averaged the mean scores and standard deviations of the three time points, which were used to define cut-off scores for subgroups of participants based on average responses across timepoints. As such, the cut-off score was not specific to one sample. For each participant, we subsequently calculated whether their scores (for the SNAT and PCG separately) were more than one standard deviation above or below the cut-off (group average score across time points). Subgroups were based on whether participants' scores exceeded 1 standard deviation (SD) on at least one of the two measures, leading to the following subgroups (see Figure 4 for the subgroup division at T1): 'strong responders' who score high on both reactive aggression and prosocial behavior (SNAT and/or PCG score >1SD above the average), 'prosocial forgivers' who score low on reactive aggression and high on prosocial behavior (SNAT score >1SD below mean and/or PCG score >1SD above the average), 'antisocial revenge-takers' who score high on reactive aggression and low on prosocial behavior (SNAT score >1SD above mean and/or PCG score >1SD below the average), and 'passive bystanders' who score low on both reactive aggression and prosocial behavior (SNAT and/or PCG score >1SD below the average). The resulting participants, whose scores did not exceed 1 SD on the measures, were labeled as the 'average group'. We divided participants into these subgroups at each time point, so groups differed in number and selection of participants across time. The subgroup division at T3 and T5 are presented in Figure S1.

First, we tested for differences between subgroups in age, sex, IQ (measured at T1 with the subtests "similarities" and "block design" of the WISC) and socio-economic status (based on parental education at T1), using separate MANOVAs for subgroups at T1, T3 and T5. Significant main effects were inspected using one-way ANOVAs and Bonferroni-corrected post-hoc tests. Secondly, we report the stability of the subgroups of social responsivity by first describing the percentage of participants that changed from subgroup, and that remained in the same subgroup between time points. Next, we tested for stability between T1 and T3, and between T3 and T5 using chi-square tests of independence on the frequency of the five subgroups. In case of significant chi-square tests, we further inspected the standardized residuals to explore the direction of the effects. P-values for the standardized residuals were Bonferroni corrected. Frequency tables including standardized residuals are reported in the supplementary materials (Table S1 and S2).

In supplementary analyses, we created the subgroups based on the difference score in noise blast duration following negative compared to positive feedback in the SNAT, to test the bidimensional model for responses to two more extreme socially salient events. We report the results of these analyses in the supplementary materials (Table S3).

Furthermore, we performed two additional sensitivity analyses. First, some participants (n=24) had negative scores on the SNAT indicating that they sent longer noise blasts following neutral compared to negative feedback. Given that these participants may not have completely understood the task instructions, we checked whether results would change when we excluded participants who scored more than two standard deviations below the average (across the three time points) in the SNAT. This led to the exclusion of 17 participants at T1 (9 passive bystanders and 8 prosocial forgivers; see Figure 4), 4 participants at T3 (3 passive bystanders and 1 prosocial forgiver) and 3 participants at T5 (1 passive bystander and 2 prosocial forgivers). Removing these participants did not alter the results. Second, we checked whether testing our linear mixed models on the four more extreme subgroups (i.e., without the average group) would change the results. Alterations from the original results are reported in the results section, all other results are reported in the supplementary materials (Table S4).

Continuous measure of social responsivity. In secondary analyses, we tested social responsivity effects by using a continuous variable of the SNAT and PCG to optimally make use of the variation between participants. We created a continuous interaction variable of reactive aggression and prosocial behavior by transforming the SNAT and PCG values (collapsed over all time points) into Z-values, adding a constant to make all Z-values positive and subsequently multiplying the SNAT and PCG values (see also Blankenstein et al., 2020; Dobbelaar et al., 2021). Higher scores indicated more social responsivity. Outliers, defined as Z-scores of <–3.29 or >3.29, were winsorized. With the use of this variable, we no longer differentiated between participants who scored high on aggression but low on prosocial behavior (i.e., antisocial revenge-takers), and the ones who scored low on aggression and high on prosocial behavior i.e., prosocial forgivers). That is, the continues measure only included one dimension (i.e., intensity of responsivity).

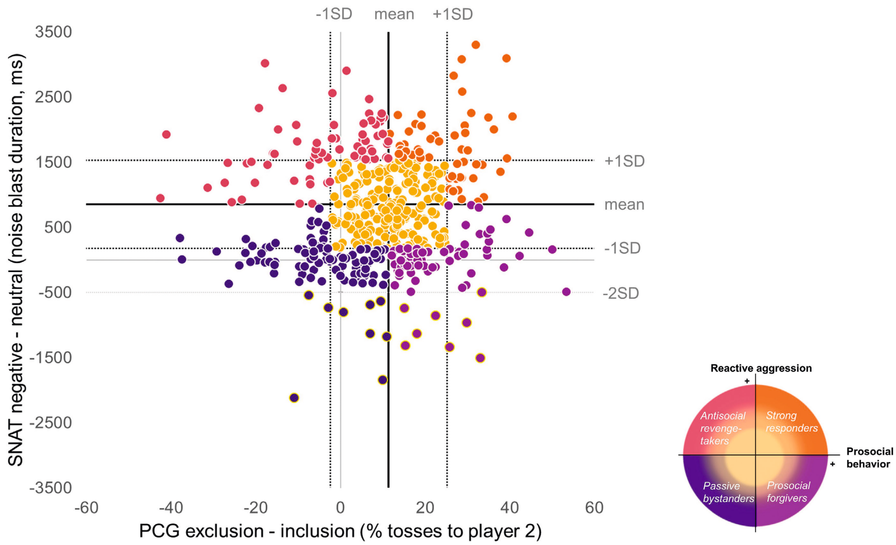

Figure 4. Division of participants into subgroups at T1. Colors indicate the different subgroups: orange = strong responders, purple = prosocial forgivers, blue = passive bystanders, pink = antisocial revenge-takers, yellow = average group. Black solid lines indicate mean scores, black dotted lines indicate one standard deviation from the mean, the light grey dotted line indicates two standard deviations below the mean on the SNAT. Individual scores below two standard deviations on the SNAT are indicated by a yellow circle.

Neural correlates of social responsivity

Subgroup analyses. We tested whether subgroups at T1, T3 and T5 differed in neural activation in the MPFC during social rejection (in the SNAT contrast 'Negative > Neutral'), experienced exclusion (in the PCG contrast 'Exclusion > Inclusion') and observed exclusion (in the PCG contrast 'Observed Exclusion > Connecting'). Parameter estimates (averaged beta values) were extracted from the subject-specific contrasts at each time point, and outliers (i.e., Z-scores of <–3.29 or >3.29) were winsorized. To test for differences in neural activation, we used a linear mixed model with subgroups added as fixed effect (5 levels: average group, strong responders, antisocial revenge-takers, passive bystanders, prosocial forgivers), and FamilyID as random factor to account for nesting of twins within families. Thus, our model was defined in R as: ROI at T1 (PE) ~ subgroups at T1 + (1|FamilyID). The same model was tested for MPFC activation and subgroups at T3 and at T5. For our primary analyses, we tested nine linear mixed model (for three ROIs at three time points).

Continuous analyses. In secondary analyses, we tested whether the continuous measure of social responsivity was related to neural activation during social rejection of self and others in the SNAT ('Negative > Neutral') and PCG ('Exclusion > Inclusion' and 'Observed Exclusion > Connecting'). Our linear mixed model for this relation at T1 was defined in R as: ROI at T1 (PE) ~ social responsivity at T1 + (1|FamilyID). The same model was tested for MPFC activation and subgroups at T3 and at T5.

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Social responsivity and associations with wellbeing

Subgroup analyses. To test whether subgroups of social responsivity in middle childhood (T1), late childhood (T3) and early adolescence (T5) predicted wellbeing (personal wellbeing and social wellbeing) at T6, we used a linear mixed model approach. Because the participants included in the subgroup differed across time points, we defined separate models for social responsivity at T1, T3 and T5. Subgroups were added as fixed effect ad sex was added as covariate. Our model was defined in R as: Wellbeing T6 ~ subgroups T1 * sex + (1|FamilyID). The same model was tested for subgroups at T3 and at T5.

Continuous analyses. In secondary analyses, we repeated the analyses on the relation between social responsivity and wellbeing, by using the continuous score of social responsivity instead of the subgroups. Thus, we defined our model for social responsivity at T1 in R as: wellbeing T6 ~ social responsivity T1 * sex + (1|FamilyID). The same model was tested for social responsivity at T3 and at T5.

RESULTS

The current study had three aims: 1) to explore stability of social responsivity; 2) to examine neural sensitivity to social responsivity, and 3) to test the association between social responsivity, environmental sensitivity and wellbeing. Results are reported along these three aims.

Stability of social responsivity

Description of subgroups

The initial set of analyses involved description of the subgroups based on the combined SNAT and PCG profiles. The sample size of each subgroup at T1, T3 and T5 is presented in Table 2. We first tested for differences in demographical variables (i.e., age, sex, IQ, and SES) between the five subgroups at T1, T3 and T5. At T1, subgroups differed in demographical variables ($F(16,2012) = 2.21$, $p = .004$, $\eta^2_p = 0.02$). Specifically, subgroups differed in age ($F(4,503) = 4.25$, $p = .002$, $\eta^2 = 0.03$): passive bystanders ($M = 7.71 \pm 0.61$) were younger than strong responders ($M = 8.05 \pm 0.68$), the average group ($M = 8.02 \pm 0.69$) and antisocial revenge-takers ($M = 8.00 \pm 0.64$; all $p \leq .050$). Moreover, at T1 subgroups differed in estimated IQ ($F(4,503) = 4.06$, $p = .003$, $\eta^2 = 0.03$): antisocial revenge-takers ($M = 106.4 \pm 11.7$) had a higher estimated IQ than prosocial forgivers ($M = 100.8 \pm 10.7$) and passive bystanders ($M = 101.4 \pm 125$; all $p \leq .045$). Subgroups did not differ on demographical characteristics at T3 ($F(16,1784) = 1.03$, $p = .417$, $\eta^2_p = 0.01$) nor at T5 ($F(16,1312) = 1.55$, $p = .075$, $\eta^2_p = 0.02$).

In addition, descriptive results show a decrease in the percentage of participants in the passive bystander group between T1 and T3 and in the antisocial revenge-takers group between T3 and T5. The percentage of participants in the average group increased between T1 and T5 (Table 2).

Table 2. Number of participants in each social responsivity subgroup at T1, T3 and T5.

	T1		T3		T5	
	N	%	*N*	%	*N*	%
Strong responders	56	11.0	66	14.5	39	11.6
Prosocial forgivers	69	13.5	50	11.0	46	13.7
Passive bystanders	97	19.0	36	7.9	24	7.2
Antisocial revenge-takers	76	14.9	68	14.9	18	5.4
Average group	212	41.6	235	51.6	208	62.1

Stability of subgroups

To study the stability of subgroups, we examined how many participants remained in the same subgroup or changed from subgroups between time points (Figure 5). Of the sample of participants with data on three time points (n=330), 18.8% of the participants remained in the same subgroup at all three time points (n=62; average group: n=57, strong responders: n=4, passive bystanders: n=1), whereas 81.2% of the participants changed subgroups at least once (n=268).

More specifically, between T1 and T3, 29.0% (n=149) of the total sample remained in the same subgroup, 58.9% (n = 303) changed from subgroup, and 12.1% (n=62) had missing data at T1 or T3. Chi-square tests indicated that the subgroups at T1 were not independent from the subgroups at T3 ($\chi^2(16) = 29.29$, $p = .022$). However, there were no significant standardized residuals between subgroup combinations (all $p >$ .057; Table S1).

Between T3 and T5, 26.7% (n=137) of the total sample remained in the same subgroup, 37.5% (n=193) changed from subgroup, and 35.8% (n=184) had missing data at T3 or T5. Chi-square tests indicated that the subgroups at T1 were independent from the subgroups at T3 ($\chi^2(16) = 22.16$, $p = .138$). There were no significant standardized residuals between subgroup combinations that survived Bonferroni correction (all p > .005, Table S2). Thus, these results indicate instability of subgroups over time.

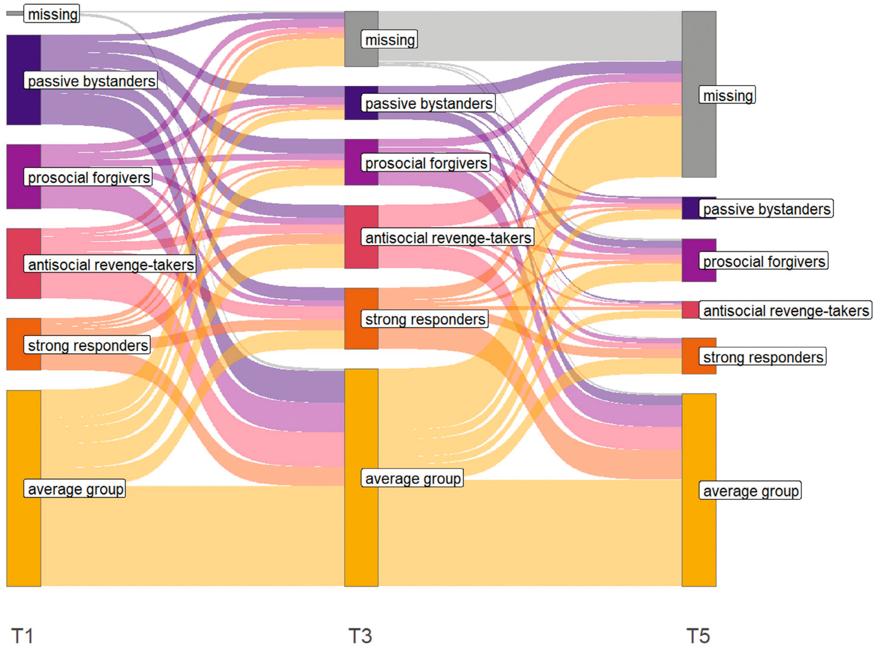

Figure 5. Stability and change of the subgroups of social responsivity at T1, T3 and T5 (n=514). Colored blocks indicate the number of participants in each subgroup at the specific time point. Lines between blocks indicate the number of participants that changed to another subgroup (or stayed in the same subgroup) at the next time point. Grey blocks indicate missing participants.

Neural correlates of social responsivity

Subgroups of social responsivity

To study whether the five subgroups differed in neural activation during social rejection, experienced exclusion and observed exclusion, we tested for subgroup effects on MPFC activation in the SNAT (social rejection; contrast negative > neutral) and in the PCG (experienced exclusion: contrast exclusion > inclusion; observed exclusion; contrast observed exclusion > connecting). The number of participants per subgroup included in these analyses are reported in Table S5.

MPFC activation during social rejection. First, we tested whether subgroups differed in MPFC activation when receiving negative compared to neutral feedback in the SNAT (negative > neutral). Subgroups did not differ in MPFC activation at T1 ($F(4,382) = 0.08$, $p = .990$, $\eta^2_p = 0.00$), nor at T3 ($F(4,352.7) = 1.91$, $p = .108$, $\eta^2_p = 0.02$). At T5, subgroups significantly differed in MPFC activation ($F(4,222) = 3.10$, $p = .016$, η^2_p

= 0.05). Bonferroni-corrected post-hoc tests indicated that prosocial forgivers higher mPFC activation compared to passive bystanders (p = .009; see Figure 6e).

MPFC activation during experienced exclusion. Second, we tested whether subgroups differed in MPFC activation when being excluded compared to being included in the PCG (exclusion > inclusion). Subgroups did not differ in MPFC activation at T1 ($F(4,271) = 0.48$, $p = .754$, $\eta^2_p = 0.01$), nor at T3 ($F(4,272.01) = 0.76$, $p = .555$, $\eta^2_p = 0.01$), nor at T5 ($F(4,186.86) = 1.10$, $p = .357$, $\eta^2_p = 0.02$).

MPFC activation during observed exclusion. Third, we tested whether subgroups differed in MPFC activation when observing exclusion of player 2 versus when observing connecting with the excluders by player 2 in the PCG (observed exclusion > connecting). At T1, subgroups significantly differed in MPFC activation ($F(4,271) = 3.08$, $p = .017$, $\eta^2_p = 0.04$). Bonferroni-corrected post-hoc tests indicated that the average group (p = .032) and prosocial forgivers (p = .048) showed higher mPFC activation than antisocial revenge-takers (Figure 6d). Subgroups did not differ in MPFC activation at T3 ($F(4,271.3) = 1.14$, $p = .338$, $\eta^2_p = 0.02$), nor at T5 ($F(4,188.4) = 1.36$, $p = .248$, $\eta^2_p = 0.03$).

Continuous measure of social responsivity

In secondary analyses, we tested whether social responsivity, as measured with the continuous interaction term (SNAT*PCG), was related to MPFC activation during social rejection in the SNAT and experienced and observed exclusion in the PCG.

MPFC activation during social rejection. At T1, social responsivity (SNAT*PCG) was associated with MPFC activation during social rejection in the SNAT ($F(1,326) = 4.88$, $p = .028$, $\eta^2_p = 0.01$), such that children who showed higher social responsivity showed less MPFC activation during social rejection feedback relative to neutral feedback ($r = -0.12$; Figure 6c). Social responsivity did not predict MPFC activation during social rejection at T3 ($F(1, 297.63) = 0.35$, $p = .556$, $\eta^2_p = 0.00$) nor at T5 ($F(1, 184) = 0.11$, $p = .738$, $\eta^2_p = 0.00$).

MPFC activation during experienced exclusion. Social responsivity was not associated with MPFC activation during experienced exclusion in the PCG (exclusion > inclusion) at T1 (F(1,233.96 = 0.15, $p = .703$, $\eta^2_p = 0.00$), at T3 ($F(1,228) = 3.63$, $p = .058$; $\eta^2_p = 0.02$) and at T5 ($F(1,155.4) = 0.18$, $p = .669$; $\eta^2_p = 0.00$).

MPFC activation during observed exclusion. At T1, social responsivity was predictive of MPFC activation during observed exclusion in the PCG (observed exclusion > connecting; $F(1,2344) = 5.89$, $p = .016$; $\eta^2_p = 0.02$), such that children who showed higher social responsivity showed more MPFC activation during observed exclusion relative to connecting ($r = 0.16$; Figure 6b). There were no significant relations between social responsivity and mPFC activation at T3 ($F(1,227.74) = 0.02$, $p = .901$; $\eta^2_p = 0.00$) and at T5: $F(1,158.48) = 0.35$, $p = .554$; $\eta^2_p = 0.00$).

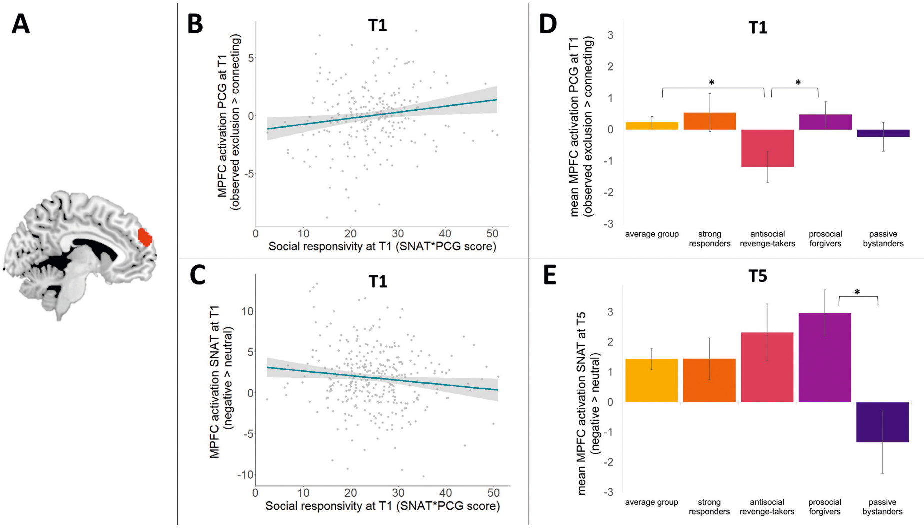

Figure 6. A) mPFC region of interest (based on Crone et al. (2020). B) Correlation between social responsivity and mPFC activation during observed exclusion (PCG observed exclusion > connecting) at T1. C) Correlation between social responsivity (SNAT*PCG scores) and mPFC activation during social rejection (SNAT negative > neutral) at T1. D) mPFC activation during observed exclusion (PCG observed exclusion > connecting) at T1. Error bars represent standard errors, * p<.05. E) mPFC activation during social rejection (SNAT negative feedback > neutral feedback) for the different subgroups at T5. Error bars represent standard errors, * p<.05.

Social responsivity and associations with wellbeing

Social responsivity and wellbeing

Subgroups of social responsivity. Next, we tested whether the five subgroups at T1, T3 and T5 predicted wellbeing (personal and social) at T6. Wellbeing at T6 was not predicted by the subgroups at T1 (personal wellbeing: $F(4,228.03) = 1.28$, $p = .279$, $\eta^2_p = 0.02$; social wellbeing: $F(4,249.48) = 0.62$, $p = .651$, $\eta^2_p = 0.01$), nor by the subgroups at T3 (personal wellbeing: $F(4,239.16) = 2.10$, $p = .082$, $\eta^2_p = 0.03$; social wellbeing: $F(4,255.01) = 0.94$, $p = .440$, $\eta^2_p = 0.01$), nor by the subgroups at T5 (personal wellbeing: $F(4,226.72) = 0.97$, $p = .422$, $\eta^2_p = 0.02$; social wellbeing: $F(4,246.39) = 0.32$, $p = .864$, $\eta^2_p = 0.01$). In sensitivity analyses on the four subgroups (i.e., without the average group), personal wellbeing was predicted by the subgroups at T3 ($F(3,93.37) = 4.49$, $p = .005$, $\eta^2_p = 0.13$), such that strong responders reported higher wellbeing than antisocial revenge-takers ($p = .009$).

Continuous measure of social responsivity. Personal wellbeing at T6 was predicted by the continuous measure of social responsivity (SNAT*PCG) at T5 (F(1,208.71) = 4.00, p = .047, η^2_p = 0.02), such that more social responsivity at T5 was related to higher personal wellbeing at T6 (r = 0.13; Figure 7). Personal wellbeing was not predicted by social responsivity at T1 (F(1,186.41) = 0.57, p = .453, η^2_p = 0.00), nor at T3 (F(1,198.28) = 0.44, p = .508, η^2_p = 0.00). Social wellbeing at T6 was not predicted by the continuous measure of social responsivity (T1: F(1,211.20) = 1.84, p = .176, η^2_p = 0.01; T3: F(1, 211.35) = 2.09, p = .150, η^2_p = 0.01; T5: F(1,227.10) = 0.79, p = .376, η^2_p = 0.00).

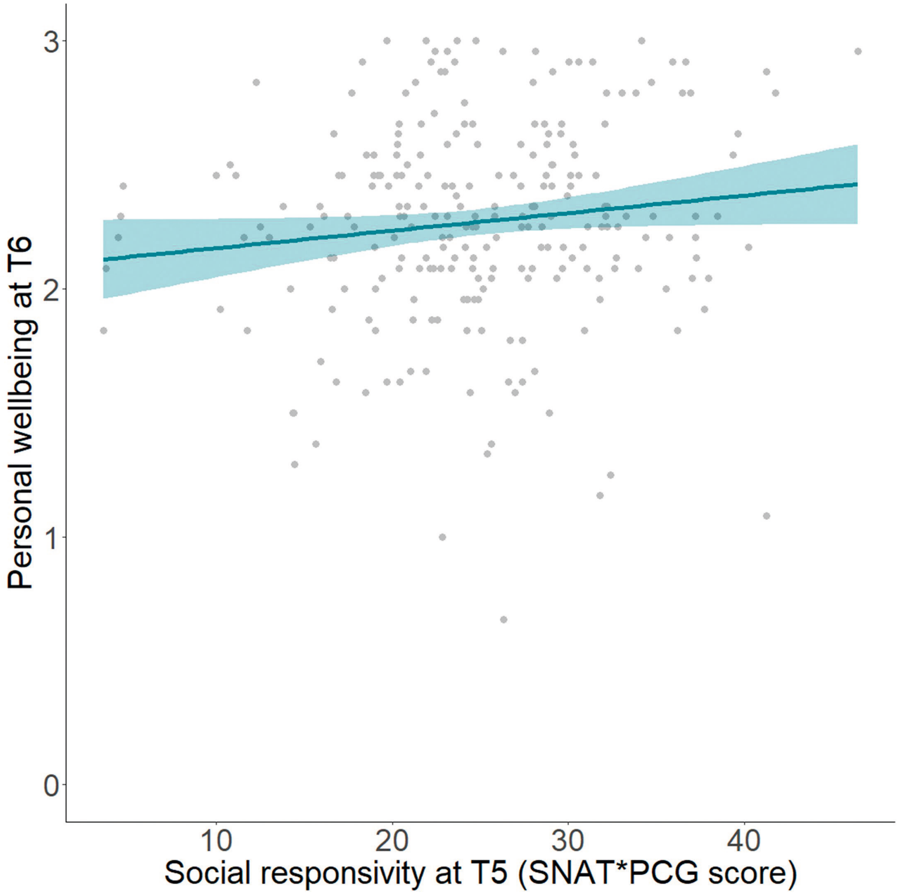

Figure 7. Association between social responsivity at T5 and personal wellbeing at T6.

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DISCUSSION

The period between childhood and adolescence is a formative period for social adaptive development, such as responding to rejection of self and others. This study examined developmental patterns, neural correlates and developmental outcomes of social responsivity, defined as the co-occurrence of prosocial behavior and reactive aggression in the transition from middle childhood to early adolescence. Our results revealed three main findings. First, we found instability of subgroups of social responsivity over time, with more than 80% of individuals changing subgroups at least once across a five-year period. Moreover, towards adolescence, the number of individuals in the more extreme socially responsive groups decreased, and participants seemed to conform towards the average group. Second, social responsivity was associated with mPFC activation during rejection of self and others, indicating a possible neural mechanism underlying socially responsive behaviors in childhood. Specifically, in middle childhood, social responsivity was associated with decreased mPFC activation during social rejection of self and with increased mPFC activation during observed exclusion of others. Third, we found that social responsivity in early adolescence was positively predictive of personal but not social wellbeing one year later, thereby highlighting the multidimensionality of wellbeing.

Stability of social responsivity

The first aim of our study was to explore the stability of subgroups of social responsivity from middle childhood towards early adolescence (e.g., Haselager et al., 2002; Magson et al., 2022). Our results revealed low stability of subgroups, highlighting that social responsivity in childhood is not necessarily predictive of responsivity in adolescence. Studies on separate developmental trajectories of aggression and prosocial behavior also often report between-person differences in developmental trajectories (e.g., Harachi et al., 2006; Nantel-Vivier et al., 2009; Piquero et al., 2012; Underwood et al., 2009). Moreover, our findings showed substantial transitions between subgroups of social responsivity over time. First, the percentage of participants in the passive bystander group (i.e., low on both aggression and prosocial behavior) decreased from 19% to 7.9% between middle and late childhood. Possibly, as reciprocity and the internalization of fairness norms largely develop in middle and late childhood (House, 2018; McAuliffe et al., 2017; van den Bos et al., 2010; Westhoff et al., 2020), aggression or prosocial behaviors following rejection may be more easily considered as the fairness norm (McAuliffe et al., 2017; Strauß et al., 2021), resulting in less passive bystander behavior. In addition, the percentage of participants in the antisocial revenge-takers group (i.e., high on aggression / low on prosocial behavior) decreased from 14.9%

to 5.4% between late childhood and early adolescence, which is in line with general decreasing patterns of reactive aggression in this period (Cui et al., 2016; Fite et al., 2008). Third, the percentage of participants in the average group gradually increased 41.6% to 62.1% between childhood and early adolescence. Early adolescence is a period of heightened sensitivity to peer influences with peaks in conformity behavior (Blakemore & Mills, 2014; Laursen & Veenstra, 2021; van Hoorn, Fuligni, et al., 2016), where adjusting to the average social norm may be especially important. It is also possible that the relatively low stability of subgroups of social responsivity is partly explained by the use of experimental tasks. Behavior in state-like paradigms such experimental tasks may be generally less stable over time compared to trait-like measures such as questionnaires (e.g., Zondervan-Zwijnenburg et al., 2022), but are specifically useful to test context-specific behaviors in social situations, such as social responsivity. Taken together, this study revealed low stability in social responsivity but also developmental transitions towards fairness norms, less reactive aggression and social conformity.

Neural correlates of social responsivity

To unravel neural mechanisms underlying social responsivity, our second aim was to test whether subgroups of social responsivity (i.e., reactive aggression and prosocial behavior) differed in activation in the mPFC when receiving social rejection feedback in the SNAT, when being excluded in the PCG and when observing exclusion of others in the PCG. Contrary to our expectations, we found that children who were less socially responsive in their behavior showed more mPFC sensitivity to social rejection in middle childhood. Importantly, in our study we specifically focused on aggressive and prosocial behaviors, that are directed outwards. Rejection can also lead to internalizing behaviors, such as feelings of anxiety (Rodman et al., 2017; Sebastian et al., 2010) and increased mPFC sensitivity to rejection feedback has also been found in internalizing disorders (Rappaport & Barch, 2020). Thus, it is possible that children who show increased mPFC activity following social rejection internalize rejection more and are therefore less socially responsive, or vice versa. Future studies may incorporate measures of subjective feelings to test whether lower social responsivity is indeed related to increased internalizing behaviors.

Subgroup analyses on neural correlates of observed exclusion revealed that prosocial forgivers (who are prosocial but not aggressive) showed more mPFC activation during observed exclusion compared to antisocial revenge-takers (who are aggressive but not prosocial), in line with prior work showing associations between increased mPFC activation during observed exclusion and subsequent prosocial behavior (Masten et al., 2011). The mPFC has often been implicated in other-focused processes such as thinking about other people's mental state and intentions, specifically in children and adolescents (Blakemore, 2008; Fehlbaum et al., 2022). As such, increased mPFC activation in the prosocial forgivers may indicate increased understanding of feelings or empathy towards the excluded peer. Additionally, continuous analyses showed that increased social responsivity in middle childhood was associated with increased mPFC activation during observed exclusion. Possibly, children who are more sensitive to other-focused emotions may be better able to adapt their behavior based on the situation. Indeed, studies on the co-occurrence of aggression and prosocial behavior suggested that both behaviors can be used to achieve social goals (Hawley, 1999). In addition, paying attention to others' needs (i.e., standing up for excluded others) can come at the cost of getting rejected yourself. Thus, children who use both aggression and prosocial behavior may be mostly other-focused and less sensitive to rejection feedback to oneself, which could explain the opposing relations of social responsivity with mPFC activation during social rejection and observed exclusion in middle childhood. However, given that the mPFC has been implicated as key region in many social behaviors (Blakemore, 2008; Crone et al., 2020; Crone & Fuligni, 2020; Somerville, 2013), adding a subjective measure of feedback sensitivity may help to further shed light the specific role of the mPFC.

Additionally, in early adolescence only, subgroup analyses on mPFC activation during social rejection revealed that prosocial forgivers showed increased activation compared to passive bystanders in mPFC sensitivity to social rejection. Possibly, the relation between mPFC sensitivity to self-related social rejection and social responsivity changes in the transition from childhood to adolescence, where neural processes related to self- and other-focused behaviors become more intertwined (Crone & Fuligni, 2020). However, given the relatively smaller sample sizes of the passive bystander subgroup (n=15) at the fifth time point, these results should be interpreted with caution.

Notably, we did not find associations between social responsivity and mPFC activation during experienced exclusion in the PCG. This suggests that neural sensitivity to receiving direct rejection peer feedback, being excluded in a group and observing exclusion in a group are distinct neural processes with differential relations to socially responsive behaviors (Achterberg et al., 2016; Premkumar, 2012; Rappaport & Barch, 2020; van der Meulen et al., 2016)

Social responsivity and associations with wellbeing

Our final aim was to examine associations with wellbeing in adolescence, to study whether behaviors in childhood and early adolescence may predict positive developmental outcomes later in time. Our findings indicated that higher social responsivity in early adolescence was associated with higher personal wellbeing one year later. This positive relation between social responsivity and personal wellbeing one year later aligns with prior studies reporting that adolescents who are both aggressive and prosocial are well-adjusted and popular (Hartl et al., 2020; Hawley, 2003), which may contribute to wellbeing. Possibly, flexible behavioral adaptation to different social contexts, as is shown by socially responsive children, may help in building social relations. Interestingly, we found an association between social responsivity and personal wellbeing but not social wellbeing, highlighting the multi-dimensional nature of wellbeing, with separate predictors for separate dimensions. Both responding aggressively when receiving negative feedback as well as acting prosocially when observing exclusion can aid in maintaining positive self-views (Crocetti et al., 2016; Rodman et al., 2017). This can in turn lead to feelings of life satisfaction and self-confidence (Cummins & Nistico, 2002; Wu et al., 2009), aspects that were mostly captured within the personal wellbeing scale. Finally, wellbeing could only be predicted by a relatively recent timepoint (T5 predicted T6) but not by earlier timepoints (T1 and T3), showing that environmental circumstances such as school transitions or the covid-19 pandemic may have influenced wellbeing as well. Future research into mediating factors such as self-concept or status among peers is needed to further increase our understanding of mechanisms underlying the link between behavioral responses to rejection and wellbeing in adolescence.

Strengths and limitations

This study took a novel approach of studying aggressive and prosocial responses to rejection of self and others as co-occurrent behaviors, instead of treating them as two separate processes. To increase our understanding of social responsivity, we used multi-modal measures, including two well-validated experimental paradigms, neuroimaging data and self-report questionnaires. Additionally, using a longitudinal sample, this study focused on the transition between middle childhood and early adolescence, thereby shedding light on a relatively understudied period in terms of neural social development.

Several limitations of the study should be acknowledged as well. First, we divided participants into subgroups based on mean scores of behaviors in a typically developing population sample. We used a mean score across the three time points to make the division less sample specific, but the cut-off is still relatively arbitrary and may differ in samples with more atypical development. Moreover, although we had a relatively large total fMRI sample size, the division of participants into separate subgroups in combination with drop-out in the longitudinal study led to relatively small subgroups at the fifth time point. To account for these issues, we additionally performed analyses using a continuous score of social responsivity. Still, to ensure that our findings are not sample specific, we emphasize the need for replication in future studies.

Second, we found a relation between social responsivity and wellbeing one year later, however, in a one-year period many possible mediating processes may be involved. An interesting approach may be to use experimental sampling methods to study whether within-person changes in social responsivity also relate to daily fluctuations in wellbeing (e.g., Beyens et al., 2021).

Finally, this study focused specifically on behaviors following rejection, but the underlying motives for responding aggressively or prosocially can differ per person and may possibly affect associations with developmental outcomes. In addition, the use of difference scores in the SNAT and PCG does not differentiate between individuals who are always or never aggressive or prosocial, even though they possibly have different social motivations for their behavior. Future studies may incorporate measures on social motives to further explore relations between social motives, behavior and wellbeing.

CONCLUSION

This study examined the co-occurrence of reactive aggression and prosocial behavior as measure of social responsivity from middle childhood to early adolescence. Our findings demonstrate that the period between middle childhood and adolescence is a transitioning phase where socially responsive behaviors are still developing and are not fixed over time. In middle childhood, social responsivity may be reflected in increased mPFC sensitivity to other-focused processes, such as observing exclusion of others, and decreased mPFC sensitivity to self-focused processes, such as receiving rejection feedback. Moreover, in addition to being a protective factor against developing behavioral problems in middle childhood (Dobbelaar et al., 2021), the current results suggest that social responsivity may also be a promotive factor for wellbeing in adolescence. These findings suggest that responding aggressively can be adaptive behavior when combined with prosocial responses and highlights the importance of studying complex social behaviors in interaction instead of as independent processes. Together, this study adds to our understanding of why some children may be more responsive to rejection than others and how these responsive behaviors may contribute to positive developmental outcomes later in adolescence.

SUPPLEMENTARY MATERIALS

Social responsivity analyses with SNAT negative – positive scores

In secondary analyses, we tested whether results would change when defining social responsivity groups based on the SNAT difference score in noise blast duration to negative and positive feedback (instead of Δ negative – neutral), i.e., the two more extreme socially salient events in the SNAT. Results of the linear mixed models on associations with mPFC activation and wellbeing are presented in Table S3. Here, we report the Bonferroni-corrected post-hoc tests of the significant linear mixed models.

Neural correlates of social responsivity

Subgroups of social responsivity. In line with results using the SNAT negative – neutral score, subgroups at T5 differed in mPFC activation during social rejection (SNAT contrast negative > neutral; Table S3): bystanders showed decreased MPFC activation compared to prosocial forgivers (p = .013), and antisocial revenge-takers (p = .025). Additionally, subgroups at T1 differed in mPFC activation during observed exclusion (PCG contrast observed exclusion > connecting): prosocial forgivers showed increased MPFC activation compared to antisocial revenge-takers (p = .016).

Continuous measure of social responsivity. Social responsivity at T1 was associated with mPFC activation during social rejection (SNAT negative > neutral; Table S3), such that higher social responsivity scores were related to decreased mPFC activation (r = -0.11). Additionally, social responsivity at T1 was associated with mPFC activation during observed exclusion (PCG observed exclusion > connecting), such that higher social responsivity was related to increased mPFC activation (r = 0.15). At T3, social responsivity was associated with mPFC activation during experienced exclusion (PCG exclusion > inclusion), such that higher social responsivity was related to increased mPFC activation (r = 0.16).

Associations with wellbeing

Subgroups of social responsivity and continuous social responsivity scores (SNAT*PCG) at T1, T3 and T5 did not predict personal or social wellbeing (see Table S3).

Social responsivity subgroup analyses on 4 subgroups

As a sensitivity check, we repeated our subgroup analyses (where subgroups were defined using SNAT negative – neutral and PCG exclusion – inclusion scores) on the four more extreme subgroups (i.e., without the average group). Results are reported in Table S4. Here, we report the Bonferroni-corrected post-hoc tests of the significant linear mixed models.

Neural correlates of social responsivity

Subgroups at T5 differed in mPFC activation during social rejection (SNAT negative > neutral; Table S4), such that prosocial forgivers showed increased activation compared to passive bystanders (p = .009). Subgroups at T1 differed in mPFC activation during observed exclusion (PCG observed exclusion > connecting), but Bonferroni-corrected post-hoc tests did not reveal significant differences between groups (all $p \geq .087$).

Associations with wellbeing

Subgroups at T3 were predictive of personal wellbeing at T6 (Table S4): strong responders reported a higher personal wellbeing than antisocial revenge-takers (p = .009). Additionally, subgroups at T5 were also predictive of personal wellbeing at T6, however, Bonferroni-corrected post-hoc tests did not reveal significant differences between groups (all $p \geq .075$).

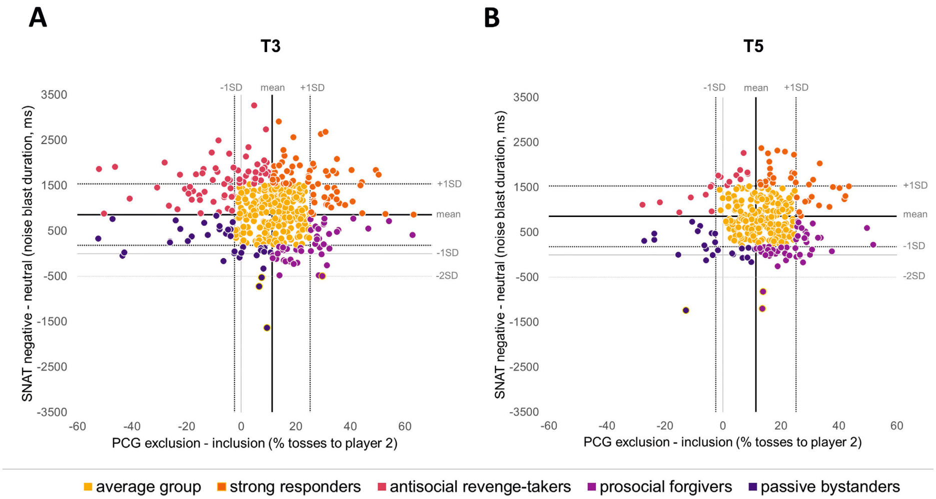

Figure S1. Division of participants into A) subgroups at T3; and B) subgroups at T5. Colors indicate the different subgroups: orange = strong responders, purple = prosocial forgivers, blue = passive bystanders, pink = antisocial revenge-takers, yellow = average group. Black solid lines indicate mean scores, black dotted lines indicate one standard deviation from the mean, the light grey dotted line indicates two standard deviations below the mean on the SNAT. Individual scores below two standard deviations on the SNAT are indicated by a yellow circle.

Table S1. Frequencies and standardized residuals between subgroups at T1 and subgroups at T3.

T1-T3		Average group T3	Strong responders T3	Prosocial forgivers T3	Passive bystanders T3	Antisocial revenge-takers T3
Average group T1	Frequency	108	20	18	10	26
	Standardized residual	1.5	-1.3	-0.5	-1.2	-0.3
Strong responders T1	Frequency	21	12	3	3	11
	Standardized residual	-0.9	1.7	-1.1	-0.5	1.3
Prosocial forgivers T1	Frequency	32	6	7	8	7
	Standardized residual	0.2	-0.9	0.1	1.5	-0.7
Passive bystanders T1	Frequency	34	14	16	12	14
	Standardized residual	-1.8	0.2	1.9	1.8	0.1
Antisocial revenge-takers T1	Frequency	37	14	6	3	10
	Standardized residual	0.2	1.2	-0.6	-1.1	-0.2

Note. * = p-value < 0.05 (uncorrected), ** = p-value < .002 (Bonferroni-correction). Yellow blocks indicate groups that remain stable over time.

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Table S2. Frequencies and standardized residuals between subgroups at T3 and subgroups at T5.

T3 – T5		**Average group T5**	**Strong responders T5**	**Prosocial forgivers T5**	**Passive bystanders T5**	**Antisocial revenge-takers T5**
Average group T3	Frequency	115	17	9	10	8
	Standardized residual	0.9	-0.6	-0.7	-0.7	-0.4
Strong responders T3	Frequency	32	10	4	3	4
	Standardized residual	-0.2	1.6	-1.2	-0.4	-0.7
Prosocial forgivers T3	Frequency	23	5	7	5	1
	Standardized residual	-0.5	0.1	0.7	1.2	-0.8
Passive bystanders T3	Frequency	11	0	8	2	2
	Standardized residual	-0.9	-1.6	2.8*	0.7	0.3
Antisocial revenge-takers T3	Frequency	25	6	6	4	3
	Standardized residual	-0.5	0.4	0.1	0.4	0.4

Note. * = *p*-value < 0.05 (uncorrected), ** = *p*-value < .002 (Bonferroni-correction). Yellow blocks indicate groups that remain stable over time.

Table S3. Results of the linear mixed models on social responsivity effects on mPFC activation and wellbeing with social responsivity subgroups and scores defined using the SNAT negative – positive difference score.

	mPFC activation									**Wellbeing at T6**					
	mPFC SNAT negative > neutral			**mPFC PCG exclusion > inclusion**			**mPFC PCG observed exclusion > connecting**			**Personal wellbeing**			**Social wellbeing**		
	F	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
Subgroups T1	0.08	4, 382	.989	0.24	4, 270.78	.918	**2.75**	**4, 271**	**.029**	1.33	4, 228.80	.260	1.28	4, 251.34	.277
Subgroups T3	1.95	4, 354.31	.102	0.90	4, 273.64	.463	1.68	4, 272.74	.155	1.36	4, 240.97	.248	0.60	4, 257.47	.661
Subgroups T5	**3.40**	**4, 222**	**.010**	1.24	4, 189.25	.297	0.58	4, 190	.674	0.93	4, 223.53	.445	0.30	4, 244.72	.876
SNAT*PCG T1	**3.87**	**1, 324.21**	**.050**	0.13	1, 233.66	.718	**5.39**	**1, 234**	**.021**	0.14	1, 187.71	.710	1.65	1, 212.40	.200
SNAT*PCG T3	0.41	1, 298.61	.522	**5.87**	**1, 228**	**.016**	0.56	1, 227.58	.453	1.52	1, 199.41	.218	0.57	1, 214.82	.452
SNAT*PCG T5	0.36	1, 184	.549	0.01	1, 159.88	.943	0.78	1, 159.94	.378	3.38	1, 203.40	.068	0.33	1, 222.91	.569

Note. Output is based on type III ANOVA's using Satterthwaite's method. Significant results are depicted in bold. Abbreviations: mPFC = medial prefrontal cortex, SNAT*PCG = continuous social responsivity score.

Table S4. Results of the linear mixed models of the social responsivity subgroup analyses on four subgroups (strong responders, antisocial revenge-takers, prosocial forgivers, passive bystanders).

	MPFC activation									Wellbeing at T6					
	MPFC SNAT negative > neutral			**MPFC PCG exclusion > inclusion**			**MPFC PCG observed exclusion > connecting**			**Personal wellbeing**			**Social wellbeing**		
	F	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
Subgroups T1	0.10	3, 218	.962	0.45	3, 149	.721	**2.74**	**3, 149**	**.045**	1.59	3, 129.35	.195	0.34	3, 159.17	.798
Subgroups T3	1.12	3, 155.68	.341	1.00	3, 129	.395	0.33	3, 122.08	.803	**4.49**	**3, 93.37**	**.005**	1.97	3, 114.94	.122
Subgroups T5	**4.09**	**3, 86.68**	**.009**	1.06	3, 76	.369	1.85	3, 76	.145	**3.36**	**3, 37.03**	**.029**	0.30	3, 94.81	.824

Note. Output is based on type III ANOVA's using Satterthwaite's method. Significant results are depicted in bold. Abbreviations: mPFC = medial prefrontal cortex.

Table S5. Number of participants in each social responsivity subgroup with fMRI data of the SNAT and PCG at T1, T3 and T5.

	T1		T3		T5	
	SNAT fMRI (n)	**PCG fMRI (n)**	**SNAT fMRI (n)**	**PCG fMRI (n)**	**SNAT fMRI (n)**	**PCG fMRI (n)**
Strong responders	45	25	58	44	30	24
Prosocial forgivers	56	39	37	26	28	25
Passive bystanders	63	46	25	20	15	12
Antisocial revenge-takers	54	39	53	39	15	15
Average group	164	122	191	145	134	114

Table S6. Items and response option of the subscales of the wellbeing questionnaires.

Wellbeing Questionnaire		response = 0	response = 1	response = 2	response = 3
Based on Multidimensional Wellbeing in Youth Scale					
1	Do you feel that you are valued by others?	not at all	not really	quite a bit	very much
2	Do you feel confident?	not at all	not really	quite a bit	very much
3	Do you feel that you are enjoying life?	not at all	not really	quite a bit	very much
4	Do you feel you get on well with your parents?	not at all	not really	quite a bit	very much
5	Do you experience feelings of happiness in everyday life?	not at all	not really	quite a bit	very much
6	Do you feel that you are loved by others?	not at all	not really	quite a bit	very much
7	Do you feel like you can talk to your friends about what's bothering you?	not at all	not really	quite a bit	very much
8	Do you feel that you are taken seriously by your parents?	not at all	not really	quite a bit	very much
9	Do you feel healthy in everyday life?	not at all	not really	quite a bit	very much
10	Do you feel happy in everyday life?	not at all	not really	quite a bit	very much
Based on World Health Organization Quality of Life Scale					
11	How would you rate your quality of life?	very bad	quite bad	quite good	very good
12	How much do you enjoy life?	not at all	not really	quite a bit	very much
13	To what extent do you feel that your life is meaningful?	not at all	not really	quite a bit	very much
14	Do you have enough energy in everyday life?	not at all	not really	quite a bit	very much
15	Do you have opportunities to relax?	not at all	not really	quite a bit	very much
16	How satisfied are you with your sleep?	very dissatisfied	dissatisfied	satisfied	very satisfied
17	Are you happy with yourself?	very dissatisfied	dissatisfied	satisfied	very satisfied

Table S6. (Continued)

Wellbeing Questionnaire		response = 0	response = 1	response = 2	response = 3
18	How satisfied are you with your personal relationships?	very dissatisfied	dissatisfied	satisfied	very satisfied
19	How satisfied are you with the support you get from your friends?	very dissatisfied	dissatisfied	satisfied	very satisfied
20	How often do you have negative feelings, such as low mood, despair, anxiety, depression? (REC)	never	sometimes	often	always
Based on subscale Social Competence from Self-Perception Profile for Adolescents					
21	(a) some teenagers find it hard to make friends, but (b) other teenagers find it pretty easy to make friends	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
22	(a) some teenagers know how to make classmates like them, but (b) other teenagers don't know how to make classmates like them (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
23	(a) some teenagers don't have the social skills to make friends, but (b) other teenagers do have the social skills to make friends	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
24	(a) some teenagers understand how to get peers to accept them, but (b) other teenagers don't understand how to get peers to accept them (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
25	(a) some teenagers know how to become popular, but (b) other teenagers don't know how to become popular (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me

Based on subscale Close Friendships from Self-Perception Profile for Adolescents

26	(a) some teenagers are able to make really close friends, but (b) other teenagers find it hard to make really close friends (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
27	(a) some teenagers don't know how to find a close friend with whom they can share secrets, but (b) other teenagers do know how to find a close friend with whom they can share secrets	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
28	(a) some teenagers do know what it takes to develop a close friendship with a peer, but (b) other teenagers don't know what to do to form a close friendship with a peer (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
29	(a) some teenagers find it hard to make friends they can really trust, but (b) other teenagers are able to make close friends they can really trust	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
30	(a) some teenagers don't understand what they should do to have a friend close enough to share personal thoughts with, but (b) other teenagers do understand what to do to have a close friend with whom they can share personal thoughts	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me

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Table S6. (Continued)

Wellbeing Questionnaire		response = 0	response = 1	response = 2	response = 3
Based on subscale Global Self-worth from Self-Perception Profile for Adolescents					
31	(a) some teenagers are often disappointed with themselves, but (b) other teenagers are pretty pleased with themselves	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
32	(a) some teenagers don't like they way they are leading their life, but (b) other teenagers do like the way they are leading their life	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
33	(a) some teenagers are happy with themselves most of the time, but (b) other teenagers are often not happy with themselves (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
34	(a) some teenagers like the kind of person they are, but (b) other teenagers often wish they were someone else (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me
35	(a) some teenagers are very happy being the way they are, but (b) other teenagers often wish they were different (REC)	(a) really true for me	(a) sort of true for me	(b) sort of true for me	(b) really true for me