NEW RESEARCH

Higher Intersubject Variability in Neural Response to Narrative Social Stimuli Among Youth With Higher Social Anxiety

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Objective: Social anxiety is associated with alterations in socioemotional processing, but the pathophysiology remains poorly understood. Movies present an opportunity to examine more naturalistic socioemotional processing by providing narrative and sensory context to emotion cues. This study aimed to characterize associations between neural response to contextualized social cues and social anxiety symptoms in children.

Method: Data from the Healthy Brain Network (final N = 740; age range 5-15 years) were split into discovery and replication samples to maximize generalizability of findings. Associations of parent- and self-reported social anxiety (Screen for Child Anxiety-related Emotional Disorders) with mean differences and person-to-person variability in functional magnetic resonance imaging–measured activation to 2 emotionally dynamic movies were characterized.

Results: Though no evidence was found to indicate social anxiety symptoms were associated with mean differences in neural activity to emotional content (fit Spearman $rs < 0.09$), children with high social anxiety symptoms had higher intersubject activation variability in the posterior cingulate, supramarginal gyrus, and inferior frontal gyrus (Bonferroni familywise error–corrected $ps < .05$)—regions associated with attention, alertness, and emotion cue processing. Identified regions varied by age group and informant. Across ages, these effects were enhanced for scenes containing greater sensory intensity (brighter, louder, more motion, more vibrance).

Conclusion: These results provide evidence that children with high social anxiety symptoms show high person-to-person variability in the neural processing of sensory aspects of emotional content. These data indicate that children with high social anxiety may require personalized interventions for sensory and emotional difficulties, as the underlying neurology differs from child to child.

Diversity & Inclusion Statement: One or more of the authors of this paper self-identifies as a member of one or more historically underrepresented racial and/or ethnic groups in science. One or more of the authors of this paper self-identifies as a member of one or more historically underrepresented sexual and/or gender groups in science. One or more of the authors of this paper received support from a program designed to increase minority representation in science. We actively worked to promote sex and gender balance in our author group. We actively worked to promote inclusion of historically underrepresented racial and/or ethnic groups in science in our author group. While citing references scientifically relevant for this work, we also actively worked to promote sex and gender balance in our reference list. While citing references scientifically relevant for this work, we also actively worked to promote inclusion of historically underrepresented racial and/or ethnic groups in science in our reference list.

Key words: emotion processing; internalizing; movie-watching; naturalistic fMRI; neurodevelopment

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Anxiety disorders are among the most common mental health problem in adults and youth.[1-3] Social anxiety in particular—characterized by fear about social situations in which the individual may be scrutinized by others[4]—has been associated with differences in social information processing.[5,6] Social information processing is the process by which people attend to, interpret, and respond to socioemotional cues in others. Recent evidence indicates that brain network activity following the onset of emotion cues varies depending on the level of social anxiety in both adults and adolescents.[7-9] However, we do not know how these differences in activation to controlled, isolated stimuli in laboratory settings translate to the real world. Considering that recent work has shown that precursors to social anxiety are present in infants,[10-12] it is critical that we identify how social anxiety is associated with emotion processing across development. Understanding both mean differences in processing and neurological heterogeneity across individuals with social anxiety would provide

important insight into the pathophysiology of social anxiety. Here, we used a large sample of functional magnetic resonance imaging collected while participants viewed videos to examine complex emotion processing differences associated with social anxiety in youth. Specifically, we examined both central tendency (ie, how social anxiety is generally associated with emotion processing) and heterogeneity (ie, how similar neural responses are between children with similar social anxiety levels) across youth.

Extensive research has found differences in emotion processing in youth and adults with social anxiety. For example, a meta-analysis of attention bias tasks using context-poor stimuli (such as emotional faces presented in isolation) found that individuals with social anxiety are quicker to attend to angry or fearful faces than neutral faces, scan angry or fearful faces longer, and look less at the eyes of emotional faces.[13] In terms of the interpretation phase of emotion processing, a meta-analysis found robust evidence for a negative interpretation bias for ambiguous information presented across myriad paradigms among individuals with social anxiety.[14] Interestingly, this work found larger negative interpretation bias effects for verbal stimuli over visual stimuli, suggesting that auditory stimuli may accentuate this effect. Taken together, these behavioral findings suggest that real-world differences in emotion processing—during which attention orienting, interpretation, and reaction are occurring rapidly and dynamically—in the brains of individuals with high social anxiety could be associated with differences in the brain networks that support these functions.

The neurological basis for these differences in real-world socioemotional processing are not yet well understood. The above work suggests differences in both the early and the automatic phases of emotional cue detection and attention orientation—functions commonly associated with primary sensory cortex, the cingulo-opercular network, and the ventral attention network[15,16]—as well as in interpretation of emotion stimuli supported by the default mode network.[17] However, previous work using context-poor emotional stimuli (such as emotional faces) found limited differences in brain activation associated with social anxiety symptoms. Meta-analyses of adult case-control neuroimaging studies show increased activation of the amygdala, insula, and medial prefrontal cortex in response to negative emotion stimuli in adults with social anxiety disorder relative to unaffected peers.[9,18,19] Similar patterns have emerged across studies of social anxiety in youth when viewing simplified or unpredictable social stimuli,[20] though with significant heterogeneity that may be task or sample dependent.[21-24] For instance, studies that use a social evaluation task (eg, the chatroom task) have found differences in striatal activation in response to social prediction error associated with social anxiety in addition to the amygdala, insula, and medial prefrontal cortex.[25-27] It is unclear, however, to what degree this pattern of results would be present for less controlled, more naturalistic stimuli. Real-world processing is, in theory, more predictable—children develop emotion reasoning skills in infancy and early childhood,[28] which they use to predict how others will feel and respond in a given situation. Social anxiety may alter or interfere with the development of this reasoning, resulting in neurodevelopmentally unique neural processing. Thus, it is possible that there is significant heterogeneity in the neurological substrates of social anxiety.

While heterogeneity of other disorders such as schizophrenia and depression is well documented, the neurodiversity associated with social anxiety phenotypes is not known, posing a barrier to treatment. Social anxiety disorder may have multiple etiologies, resulting in diverse neurological causes of the same phenotype. For example, children with social anxiety symptoms may also have heightened or otherwise atypical sensory responses,[29-33] which could lead to altered emotion reasoning development through alterations in the early phases of emotion processing. Additionally, children with early childhood behavioral phenotypes related to later social anxiety, ie, behavioral inhibition, may not have differences in sensory processing, but may instead demonstrate different patterns of cognitive processing,[12,34] altering later stages of emotion processing. Finally, parental anxiety is a strong predictor of child anxiety independent of genetic risk,[35] suggesting that parenting and other environmental factors influence the course of development of social anxiety symptoms. The degree of similarity of neural activation across individuals with social anxiety has not yet been examined, and thus it is unclear how individual differences in neural function matter for treating social anxiety symptoms. Directly assessing the degree of heterogeneity in social processing in children with high social anxiety would therefore provide important insight to the pathophysiology of social anxiety disorder, which may be obscured in traditional mean-centric analysis. Specifically, similarity analysis would indicate the degree of neurological heterogeneity within high social anxiety samples.

The present study used video stimuli to examine contextualized socioemotional processing associated with social anxiety symptoms in youth. We had three aims: to identify what patterns of activation to emotion stimuli are associated with social anxiety symptoms with respect to mean and intersubject variability; to characterize the specific scenes that elicit these associations; to test if the results of

these analyses differ as a function of developmental stage. To accomplish these aims, we leveraged a large dataset of functional magnetic resonance imaging data collected while children watched emotional video clips. We used multivariate methods and split our data into discovery and replication sets to maximize reproducibility. Our analyses were designed to characterize both patterns of activation that are systematically associated with social anxiety symptoms at the mean level (mean tendency; regression based) and the degree of heterogeneity in activation responses associated with social anxiety symptoms (sample heterogeneity; similarity based). Based on previous literature and emotion theory, we predicted variation in activation to negative emotions in attentional, default mode, and primary sensory regions of the brain to relate to social anxiety symptoms. We expected associations between activation and social anxiety symptoms to be strongest during scenes with negative emotions and increased sensory intensity. Based on previous findings that activation to emotion stimuli is largely stable across ages 5 to 15,[36] we did not predict large differences in associations between brain activation and social anxiety symptoms in older vs younger ages.

METHOD

All custom processing scripts and analysis notebooks are available on GitHub (https://github.com/catcamacho/hbn_socanx). A more detailed description of each method is included in Supplement 1, available online.

Sample and Study Information

These analyses included data from 740 participants 5 to 15 years old from the Healthy Brain Network Biobank[37] who were previously analyzed to examine developmental differences in emotion processing.[36] Briefly, children and adolescents were recruited across 4 sites in the New York area to participate in neuroimaging and clinical and cognitive assessments. The sample is enriched for boys and for children with psychopathology. Full study details are listed on the study website (http://fcon_1000.projects.nitrc.org/indi/cmi_healthy_brain_network/index.html) and summarized in Supplement 1, available online. Final sample characteristics are listed in Table 1. Data were split by collection site in training or discovery (n = 386 participants; Rutgers site) and testing or replication datasets (n = 354 participants; Cornell site) for analyses to enhance confidence in results. The testing/replication sample had participants with higher average motion, lower depression scores, and lower self-reported social anxiety scores and fewer participants with missing diagnostic data than the training/discovery sample. We accounted for differences in motion and depression scores by regressing them out.

Clinical Measures

Social Anxiety Symptoms. The Screen for Child Anxiety Related Disorders (SCARED)[41] is a 41-item questionnaire that was completed by parents for their children (all children) and by children for themselves (ages 8 and older only). The social anxiety subscale score was used for further analysis, which has a possible score range of 0 to 14, with higher scores indicating greater symptom severity. Parent- and self-reported scores were modestly correlated (Spearman $r = 0.28$, $p < .001$). Distributions of scores across age are shown in Figure S1, available online.

Depression Symptoms. The Mood and Feelings Questionnaire (MFQ)[42] is a 34-item questionnaire completed by parents for their children (all participants) and by children for themselves (ages 8 and older only). Parent- and self-reported scores were modestly correlated (Spearman $r = 0.25$, $p < .001$). As expected, social anxiety and depression scores were correlated (parent-report $r = 0.25$, self-report $r = 0.42$, $ps < .001$), as were generalized anxiety and depression scores (parent-report $r = 0.50$, self-report $r = 0.57$, $ps < .001$). We used total scores as a covariate in further analyses, matching social anxiety symptom informant.

Neural Activation to Emotional Videos

Children watched a 10-minute segment of the movie *Despicable Me* and the 3-minute 20-second Pixar short movie *The Present* during functional magnetic resonance imaging collection. Each video contained both positive and negative emotional content and had stories driven by social relationships. *Despicable Me* has a more complex story, however, as it deals with internal conflicts, children bonding with and then being separated from their adoptive parent, and hijinks from peripheral characters. *The Present* is self-contained and a simpler story of a boy receiving a puppy, rejecting the puppy, and the puppy convincing the boy to take him outside and play. Videos were coded using the EmoCodes video coding system[43] to create a time series of each broad emotion (positive, negative) and specific emotions (fearful, angry, sad, happy, excited) as well as nonemotional video features. While specific emotions (eg, angry, fearful, sad) are also captured in the broad emotion categories (eg, negative), we examined them separately for better comparison with the broader literature that used either an emotion category approach (angry, fearful) or a

TABLE 1 Demographics and Clinical Data of Sample

Characteristic	Low-motion data (N = 740)				t, χ^2, or *U*	*p*
	Discovery/training (n = 386)		Replication/testing (n = 354)			
Demographics						
	Mean	(SD)	Mean	(SD)		
Age, y	10.4	(2.6)	10.6	(2.9)	$t = 1.02$	.307
Puberty score	9.6	(4.1)	9.7	(4.2)	$t = -0.48$	.632
	n	(%)	n	(%)		
Female	139	(36)	139	(39)	$\chi^2 = 0.83$	.361
Right-handed	293	(76)	258	(73)	$\chi^2 = 0.89$	.346
Race					$\chi^2 = 10.19$	.178
	n	(%)	n	(%)		
American Indian/Alaskan Native	0	(0)	1	(0)		
Asian/Asian American	7	(2)	13	(4)		
Biracial	57	(15)	67	(19)		
Black/African American	43	(11)	49	(14)		
Native Hawaiian/Pacific Islander	0	(0)	1	(0)		
Other	5	(1)	6	(2)		
White/European American	220	(57)	178	(50)		
Unknown	54	(14)	39	(11)		
Ethnicity					$\chi^2 = 1.88$	.391
Hispanic/Latinx	95	(25)	77	(22)		
Not Hispanic/Latinx	256	(66)	251	(71)		
Unknown	35	(9)	26	(7)		
Annual household income					$U = 45{,}254$	.349
<$10,000	10	(3)	4	(1)		
$10,000-$19,999	11	(3)	9	(3)		
$20,000-$29,999	13	(3)	13	(4)		
$30,000-$39,999	16	(4)	19	(5)		
$40,000-$49,999	14	(4)	10	(3)		
$50,000-$59,999	8	(2)	10	(3)		
$60,000-$69,999	18	(5)	17	(5)		
$70,000-$79,999	10	(3)	14	(4)		
$80,000-$89,999	16	(4)	13	(4)		
$90,000-$99,999	18	(5)	13	(4)		
$100,000-$149,999	68	(18)	56	(16)		
≥$150,000	113	(29)	122	(34)		
Unknown	71	(18)	54	(15)		
	Mean	(SD)	Mean	(SD)		
Motion	0.27	(0.16)	0.43	(0.18)	$t = -15.09$	< .001
Clinical symptoms						
Self-reported social anxiety	5.3	(4.1)	4.9	(3.7)	$t = 1.19$	.236
Self-reported depression	13.5	(11.4)	11.7	(10.3)	$t = 2.06$	.040
Parent-reported social anxiety	4.4	(3.7)	3.8	(3.5)	$t = 2.24$	.026
Parent-reported depression	9.6	(8.7)	8.4	(8)	$t = 2.01$	.045
Parent-reported ADHD symptoms	0.4	(0.9)	0.3	(1)	$t = 1.45$	.149
Clinical diagnoses						
	N	(%)	N	(%)		
Depressive disorder	35	(14)	33	(13)	$\chi^2 = 0.18$	.672

(continued)

TABLE 1 Continued

Characteristic	Low-motion data (N = 740)				t, χ^2, or *U*	*p*
	Discovery/training (n = 386)		Replication/testing (n = 354)			
Anxiety disorder	119	(49)	135	(54)	$\chi^2 = 1.05$	.306
Bipolar disorder	2	(1)	0	(0)	$\chi^2 = 2.08$	.149
Disruptive disorder	51	(21)	40	(16)	$\chi^2 = 2.16$	.142
Elimination disorder	35	(14)	31	(12)	$\chi^2 = 0.47$	.491
Eating disorder	3	(1)	3	(1)	$\chi^2 = 0.00$	.964
Learning disorder	66	(27)	98	(39)	$\chi^2 = 7.69$	.006
ADHD	163	(67)	163	(65)	$\chi^2 = 0.32$	.571
Autism	45	(19)	45	(18)	$\chi^2 = 0.06$	.848
Obsessive-compulsive disorder	19	(8)	22	(9)	$\chi^2 = 0.13$	.713
Trauma or stress disorder	12	(5)	19	(8)	$\chi^2 = 1.43$	.232
No diagnosis	3	(1)	1	(0)	$\chi^2 = 1.08$	.298
Missing or incomplete	144	(37)	103	(29)	$\chi^2 = 5.60$	.018

Note: Puberty scores were obtained using the Peterson puberty index[38]; ADHD symptoms were obtained from the Strengths and Weaknesses of Attention-Deficit/Hyperactivity Disorder Symptoms and Normal Behavior questionnaire[39]; and diagnoses were obtained from clinical consensus based on the Schedule for Affective Disorders and Schizophrenia for School-Age Children[40] combined with observations and questionnaire responses. ADHD = attention-deficit/hyperactivity disorder.

valence approach to classifying emotion stimuli (negative). To test if we could replicate past work finding a mean-centric association between activation to negative emotional content and social anxiety symptoms, we used the time series regressors to estimate activation for negative, angry, and fearful content in each video. Given research showing that anxiety is associated with sensory sensitivity,[44-46] we also estimated activation to low-level brightness and loudness. See Supplement 1, available online, for a more detailed description of this method. Traces for select video content over time and scene descriptions are presented in Figure 1 and Figure S2, available online, while full features are shown in Figure S3, available online. Video feature analysis results are shown in Figures S4 and S5, available online. Nonemotional features were not significantly collinear with emotion features.

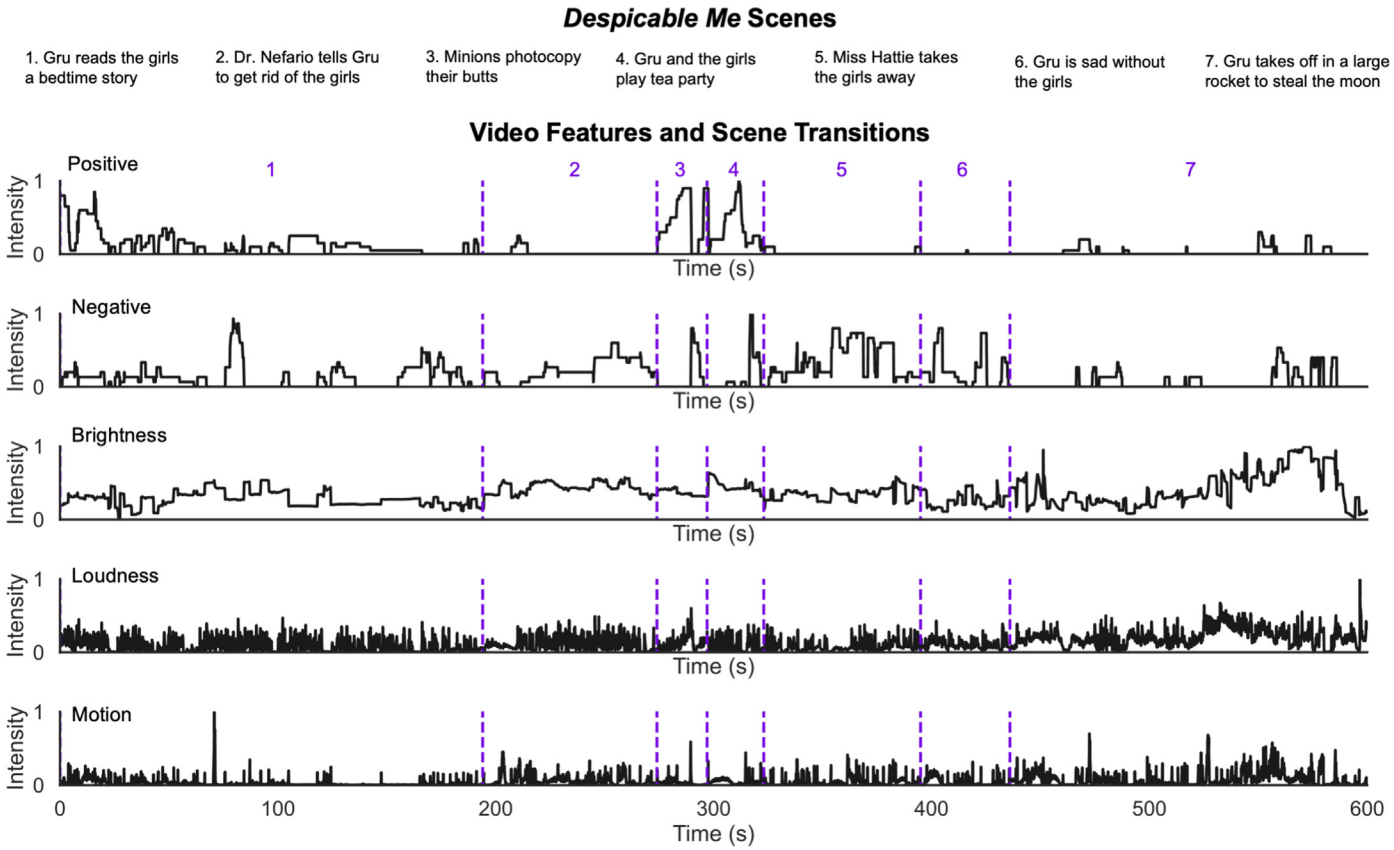
Support Vector Regression Analysis

We first tested if linear or nonlinear models could capture mean variation in activation to emotional and low-level stimuli using support vector regression (SVR). Activation maps estimated for each negative, fearful, angry, loudness, and brightness were separately used as the feature set with residualized social anxiety scores (age, sex, mean motion, and depression scores regressed out) as the feature labels. Each participant contributed 1 or 2 samples per activation map depending on if usable data were available from one or both videos. SVR models were trained on the training data using 10-fold cross-validation on each activation map. SVR model performance was then evaluated on the unseen testing dataset. Model accuracy was operationalized as the correlation and the mean squared error between the actual and predicted labels. A total of 20 models were run (5 activation map categories [negative, angry, fearful, brightness, loudness] × 2 SVR kernel models [linear, nonlinear] × 2 social anxiety score sources [parent-report, self-report]). See Supplement 1, available online, for a more detailed description of this method.

Intersubject Representational Similarity Analysis

Behavioral work suggests that social anxiety may be marked by a wide range of responses to emotional content; thus we also employed a completely model-free data-driven approach to test if there was greater or lesser intersubject similarity in activation across children with higher social anxiety compared with children with lower symptoms. To accomplish this, we employed intersubject representational similarity analysis (IS-RSA)[47] to test 3 models relating symptom level similarity and similarity of brain activation across the videos: consistent-high (higher symptoms → more similar activation); variable-high (higher symptoms → more heterogeneous activation); nearest-neighbor (similar symptoms scores → similar activation). These models were tested across the full sample as well as in younger (ages 5-10 years) and older (ages 10-15 years) splits of the data. For each analysis, social anxiety scores were

FIGURE 1 Scene Descriptions and Transitions in *Despicable Me*



Note: *Select video features are plotted with vertical dashed lines indicating scene transitions.*

residualized before analysis (regressing out age, sex, mean motion, and depression symptoms). Neural similarity was computed as parcelwise intersubject correlation. IS-RSA for each parcel was computed as the correlation between intersubject correlation and symptom similarity values. The p values were assigned by permuting the behavioral similarity scores to generate a null distribution of 10,000 values. Parcels were considered significant at $p < .05$ after Bonferroni-style familywise error correction. These procedures were repeated across videos and samples. Bootstrapped statistical distributions for each model were tested against each other for each significant parcel to determine the best-fitting and replicable model. See Supplement 1, available online, for a more detailed description of this method. For the younger and older subsample analysis, we also statistically compared the coefficient distributions between the samples using a t test.

IS-RSA were also repeated covarying attention-deficit/hyperactivity disorder symptom scores due to the high proportion of children with a lifetime ADHD diagnosis in the sample. These results were nearly identical and are reported in Supplement 2 and Figure S6, available online. We also conducted IS-RSA using the generalized anxiety scale scores from the SCARED to test if the results we observed were unique to social anxiety. These results differ extensively from our analysis of social anxiety (reported in Supplement 3 and Figure S7, available online), suggesting that these analyses are not indexing associations with anxiety more generally.

Dynamic Similarity Analysis

We next aimed to characterize when children with highest and lowest symptom scores were synchronized in brain activation across each video to parse what content evoked synchronous or heterogeneous responses. To accomplish this, we computed pairwise intersubject phase synchrony for the children with the highest scores (top 20%) and the lowest scores (bottom 20%). Of the children with diagnostic information and who were in the top 20% of social anxiety scores, 21% to 30% met criteria for lifetime social anxiety disorder, and 44% to 56% met criteria for any lifetime anxiety disorder. Parcels were limited to those identified in the IS-RSA analysis for that video and informant, averaging across all those with the same model

designation (variable-high, consistent-high, or nearest-neighbor). A t test was conducted for each time point in the series to identify when in each video the top and bottom 20% of the sample significantly differed in intersubject phase synchrony distributions, and p values were assigned using a subjectwise permutation approach. Only significant segments that were at least 4 seconds long and replicated across both samples are reported and analyzed further. Video segments identified from the time series t test analysis were next analyzed quantitatively and qualitatively to determine what kind of content induced similar patterns of activation in children with the highest or lowest symptoms as appropriate for the model identified in the IS-RSA.

Motion

An extensive analysis of motion in relation to each analysis approach, video features, and psychiatric symptoms is presented in Supplement 4, available online. In short, we have no evidence to suggest that our findings are a result of motion contamination.

RESULTS

Social Anxiety Is Not Associated With Mean Differences in Activation

Across all activation maps (negative, anger, fear, brightness, loudness), both sets of scores (self-report, parent-report), and both kernel types (linear, nonlinear), the multivariate regression models did not perform well as indicated by poor concordance between actual and predicted labels (correlation coefficients < 0.06, $ps > .104$). Full model statistics are shown in Table S1, available online. These results demonstrate a lack of mean differences in activation between children with low and high social anxiety, failing to replicate previous work using smaller samples, univariate statistics, and context-poor stimuli.

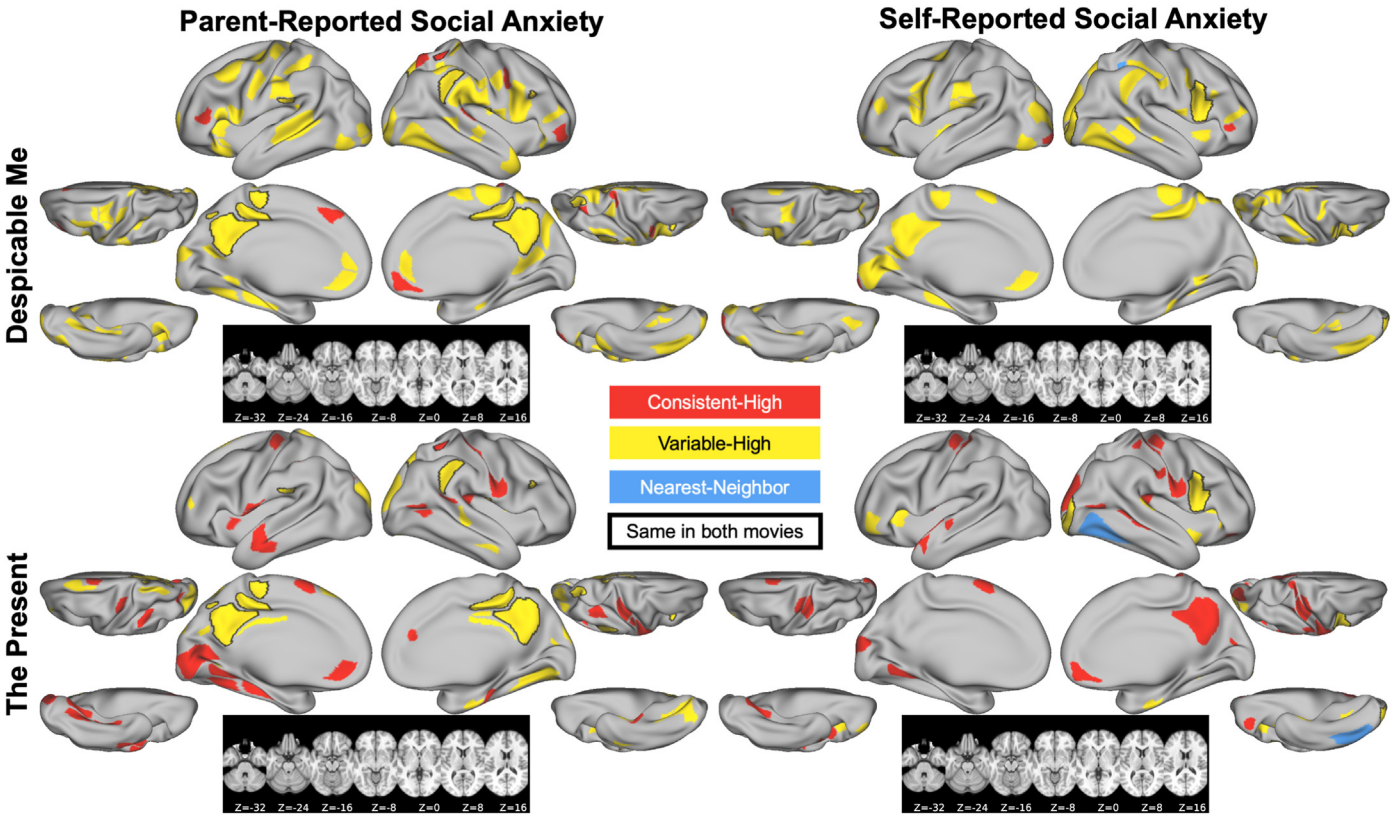
Children With Higher Social Anxiety Symptoms Have More Heterogeneous Activation Patterns to Emotional Movies Than Children With Lower Symptoms

Using intersubject representational similarity analysis, we found that increased parent-reported social anxiety symptoms were associated with greater intersubject variability in activation of 10 regions of the brain spanning the posterior cingulate, supramarginal gyrus, and premotor, dorsal parietal, and auditory cortex as indicated by the variable-high model best fitting the data across both movies and samples (Figure 2). Most of these regions fell into the default mode (2 parcels), cingulo-opercular (4 parcels), and dorsal attention (2 parcels) networks with one parcel each in the somatomotor and frontoparietal networks. Only one parcel in the postcentral gyrus best fit the consistent-high model (more consistent activation across children with higher symptoms). For the self-reported social anxiety analysis, we found the same pattern of increased symptoms associated with more variable activation patterns across children; however, only 2 parcels were replicated across videos and samples. One parcel was in the right lateral occipital lobe in the visual network, and the other was in the right dorsal inferior frontal gyrus in the dorsal attention network, adjacent to the parcel identified in the parent-report model (Figure 2). Significant parcels were more consistent for parent-reported symptoms both between samples within the same movie (parent-report overlap: *Despicable Me*, 42%; *The Present*, 33%; self-report overlap: *Despicable Me*, 33%; *The Present*, 14%) and between movies (parent-report overlap: 25%; self-report overlap: 8%), but all overlaps were greater than chance ($\chi^2 > 19.67$, $ps < .001$). Statistical maps for the variable for parcels that replicated across samples are shown for each movie in Figure 2. When the data were limited to the younger (5-10 years old) or older (10-15 years old) sample, a similar pattern emerged with the variable-high model providing the best fit to the data for most parcels spanning cingulo-opercular, default, and attention network regions, with some variation in the specific regions (Figures S8 and S9, available online). The statistical comparison of the dominant model (variable-high) coefficients between the older and younger subsamples found that there was no difference between ages for *Despicable Me* ($t = 1.15$, $p = .252$) and that there was a stronger variable-high effect in the older children for *The Present* ($t = 2.70$, $p = .009$). Overall, these results show that higher symptoms are associated with more intersubject heterogeneity in activation during naturalistic emotion processing in regions associated with attentional and higher order sensory processing both for younger children and for older youth.

Scenes With Higher Sensory Intensity Evoke Heterogeneous Activation Among Children With High Symptoms

To infer what combination of stimuli elicits greater intersubject activation heterogeneity among children with higher social anxiety symptoms, we compared the intersubject phase synchrony distributions between children with the lowest and highest symptoms as reported in each symptom questionnaire (self- or parent-report) across the parcels that best fit the variable-high model for each video. Across informants, there was greater intersubject activation variability among children with high symptoms than children with low symptoms for approximately half of *Despicable Me* (46% of the running time for self-report, 53% for parent-report), which included scenes that were on average brighter and more vibrant with less emotional content (Figure 3;

FIGURE 2 Results From the Intersubject Representational Similarity Analysis (IS-RSA) Model Fit Comparisons



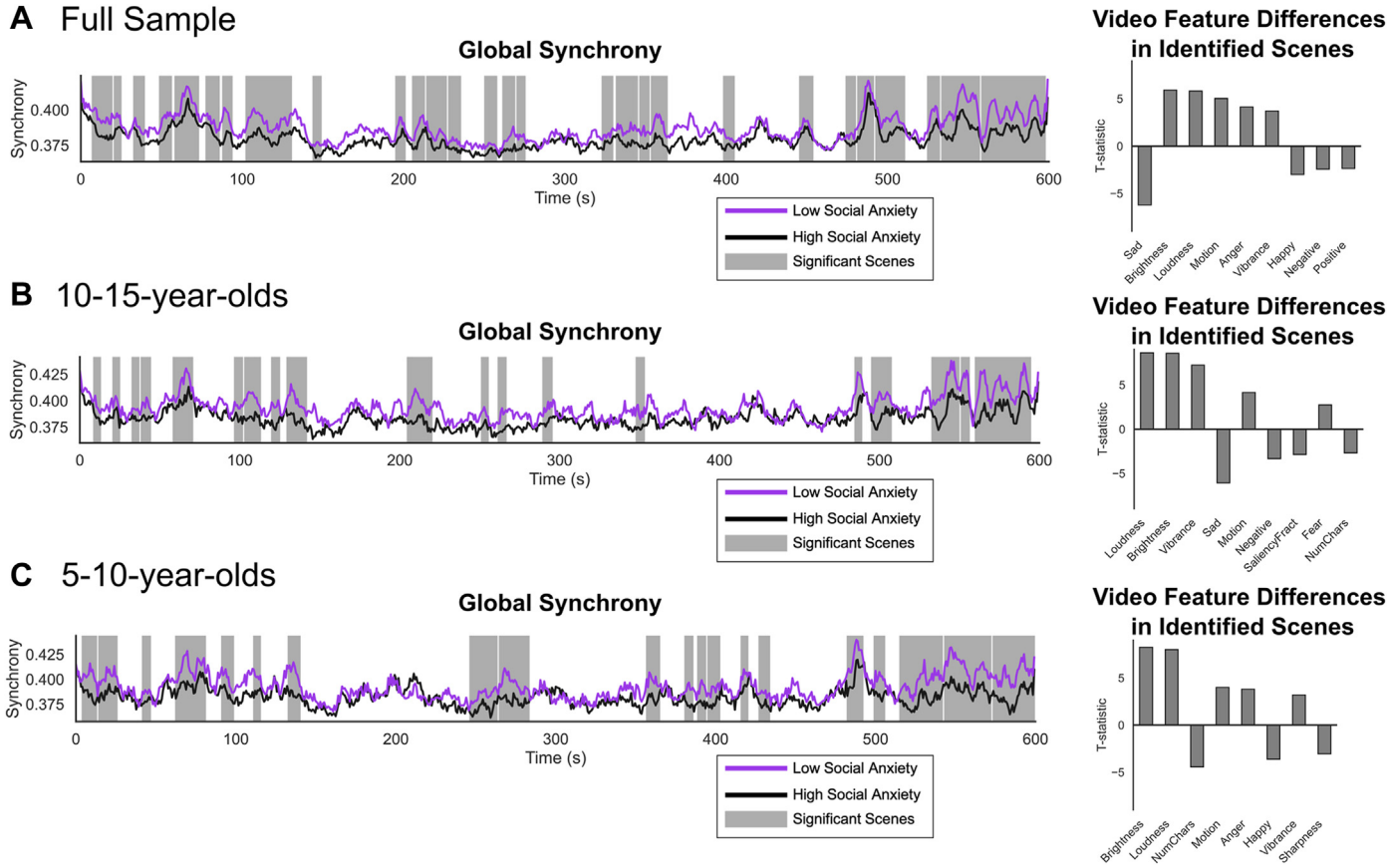
Note: *Results for parent-reported social anxiety are shown on the left, and results for self-reported social anxiety are shown on the right. The variable-high model was the dominant one, indicating that there was greater heterogeneity in activation patterns among high symptom children than among low symptom children. Models controlled for age, sex, mean motion, and depression scores. Consistent-High = greater interpersonal synchrony in higher symptom children; Variable-High = less interpersonal synchrony in higher symptom children; Nearest-Neighbor = greater synchrony in children with similar levels of social anxiety symptoms.*

Figure S10, available online). When we repeated these analyses within each age group, we found that 36% of the identified scenes overlapped. Though different portions of the video were identified between age groups, the scenes were on average brighter, louder, and more vibrant; had more motion; and had fewer characters in both age groups (Figure 3). There was greater intersubject synchrony in children with low parent-reported social anxiety symptoms compared with children with higher symptoms in 5 scenes in *The Present.* No scenes in *The Present* were identified for self-reported social anxiety. Results are shown in Figures S11 and S12, available online.

DISCUSSION

This study sought to characterize the association between social anxiety symptoms and activation to emotional videos in a large sample of children 5 to 15 years old. We found no mean differences in activation patterns between children with high and low social anxiety, failing to replicate previous studies that examined smaller samples and used decontextualized emotional stimuli. Using similarity analysis, we found that across both videos and samples there was greater heterogeneity in activation patterns among children with higher social anxiety symptoms compared with children with lower symptoms. The specific regions showing more variable activation were primarily in the cingulo-opercular, attentional, and default mode networks. Dynamic similarity analysis revealed that for the longer video (*Despicable Me*), scenes with higher sensory intensity (greater brightness, loudness, vibrance, and motion) aligned with periods of greater activation variability between children with higher symptoms relative to children with lower symptoms. This finding suggests that increased sensory intensity may induce a wider range of activation patterns in children with higher social anxiety symptoms. These results were in contrast to an identical analysis of generalized anxiety, suggesting that this pattern of greater heterogeneity is unique to social

FIGURE 3 Dynamic Similarity Results for *Despicable Me*, Comparing Children Highest (Top 20%) and Lowest (Bottom 20%) in Parent-Reported Social Anxiety Symptoms



Note: *Line plots: The shaded portion of each time series indicates the video segment during which between-subject activation similarity significantly differed between low and high symptom children (p < .05 for at least 4 seconds and in both samples). Video feature analysis: Bar plot with video features significantly different in the identified scenes compared with the rest of the video (Benjamini-Hochberg false discovery rate–corrected p < .05).*

anxiety rather than reflecting broader associations with anxiety. When we limited data to specific age groups, the same dominant pattern of greater heterogeneity in activation between the children with high symptoms was observed across age groups as well as a similar pattern of scenes of higher sensory intensity being associated with significant differences in intersubject activation similarity. Taken together, our results suggest a weak association between the emotional content of social stimuli and social anxiety symptoms. Instead, increased sensory intensity was more consistently associated with differences in cingulo-opercular, default, and attentional network intersubject synchrony in children with low vs high symptoms.

We found that for children with higher symptoms, scenes associated with greater intersubject variability had higher sensory intensity. While limited, there is previous research finding oversensitivity to sensory stimuli to be associated with anxiety levels in children, with tactile and auditory sensitivity being commonly reported.[32,33] It is therefore possible that previous work reporting differences in activation or behavior on the basis of emotional content actually detected differences in saliency and sensory processing present in individuals with high social anxiety. For example, scenes with increased sensory intensity could induce more variable fixations across the screen, which may translate to differences in activation, an effect that may be magnified in children with social anxiety. A testable theory is the possibility that sensory information interferes in emotion processing in children with heightened anxiety symptoms, and the underlying neurobiology may differ as a function of when these symptoms interact with neurodevelopment. For instance, sustained behavioral inhibition early in infancy may develop into social anxiety symptoms, while acquired social anxiety as a result of traumatic experience could emerge at any point later in development. Social anxiety presenting when children are learning which cues are important to attend to (early development), as opposed to when learning a shared understanding of social

situations (later in development), may reinforce different neural pathways, leading to diverse neural responses to the same social stimuli later in life. Future work must tease apart how social anxiety is associated with sensory, attentional, and emotional processing across development.

Our findings have important implications for how we understand the phenomenology of social anxiety. Specifically, our findings suggest greater heterogeneity in the underlying neural phenomenon than has been previously appreciated, indicating that more personalized approaches for both studying and treating social anxiety are warranted. This adds to recent work suggesting a cognitive neurodevelopmental framework, which would explain heterogeneity in the neurobiology underlying social anxiety. Specifically, differences in the lived experiences between children during different developmental periods can result in unique neurobiological underpinnings to similar behaviors. Considering that we found the variable-high model to be the best fit across age groups, our findings add to the body of work suggesting that mapping neurodevelopment during infancy and early childhood is of particular importance for understanding the etiology of anxiety.[48] For instance, the dual process model[34] posits that social anxiety may develop from early behavioral inhibition via heightened automatic processing that fails to integrate effectively with top-down cognitive processes across development, resulting in automatic processes dominating social information processing.[12] Considering the evidence that individuals with social anxiety take longer to habituate to salient stimuli,[49,50] it is likely then that children with social anxiety would not learn to cope with heightened sensory situations as effectively as their unaffected peers, influencing the early stages of social processing in a manner that is highly specific to the lived experiences of each child. Children with high social anxiety who live in a noisy household, for example, may be able to acclimate to louder movie scenes similarly to their unaffected peers, but not to sudden shifts in brightness. Similarly, children with social anxiety who have experienced trauma may exhibit overactive automatic processing that is further heightened following negative emotion cues, resulting in different activation patterns to high sensory intensity scenes that also have negative emotions. More research examining how specific activation patterns develop in conjunction with both early affective neurobiology and individual experiences is needed to test these theories of how the neurobiological heterogeneity in children with high social anxiety that we observed emerges.

This study has several innovative strengths that build on previously published works as well as important limitations to consider. First, we characterized emotional processing using complex video stimuli, increasing ecological validity of our results by mimicking complex emotion processing. Second, we examined a large dataset that we divided into discovery and replication samples to enhance reproducibility and confidence in our results. Finally, we examined both self- and parent-reported symptoms, providing a clearer picture of how our findings fit into the extant literature as well as how informant may affect what brain–behavior associations are found. There are also several limitations to this study. First, this is a cross-sectional study. Even though we repeated analyses within age groups, we cannot draw any conclusions regarding the intersection of neurodevelopment and social anxiety symptoms. Second, we relied on use of questionnaires for our measurement of social anxiety symptoms, which is not as rich as direct observations. Thus, we interpret our findings broadly and urge future researchers to include behavioral assays of social anxiety symptoms in their work to better capture objective individual differences. Third, while movies are more naturalistic than traditional tasks, movie are not perfect mimics of real-life social processing. Filmmakers manipulate cinematography to evoke specific feelings, and animated movies can change music and color palettes to evoke certain moods. Nonetheless, examining differences in movie watching lends insight to more naturalistic socioemotional processing. Fourth, while we adhered to rigorous best practices to minimize overfitting, it is still important to replicate these findings in separate samples before drawing broad conclusions. Finally, there were no consistent significant differences in video features of the scene identified in *The Present*. This may be due to the shorter nature of the clip (*The Present* is just over 3 minutes long, while a 10-minute clip from *Despicable Me* was used) or because *The Present* is less dynamic in terms of brightness, loudness, and motion compared with *Despicable Me*. Future work should examine activation to several video clips with varied sensory and social content to draw broader conclusions.

In summary, we found evidence that increased social anxiety symptoms in children are associated with greater variability in activation during viewing of emotionally dynamic videos. The specific regions that show this pattern varied by age and informant. Intriguingly, increased sensory intensity on the screen was associated with greater intersubject activation variability in the children with highest symptoms compared with the children with lowest symptoms, but the presence of negative affect was not. These results provide insight into the complex relation between social anxiety symptoms and real-world socioemotional processing. Further work is needed to connect developmentally sensitive objective measures of social anxiety with naturalistic emotion processing to better understand how these symptoms affect child development and functioning.

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Investigation: Camacho
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