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Higher inter-subject variability in neural response to narrative social stimuli among youth with higher social anxiety

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Abstract

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

Method: We used data from the Healthy Brain Network (final N=740; ages 5–15 years), split into Discovery and Replication samples to maximize generalizability of findings. We characterized how each parent- and self-reported social anxiety (Screen for Child Anxiety-related Emotional Disorders) are associated with each mean differences and person-to-person variability in fMRI-measured activation to two emotionally dynamic movies.

Results: Whereas we found no evidence that social anxiety symptoms were associated with mean differences in neural activity to emotional content (fit Spearman rs<0.09), children high in social anxiety symptoms had higher inter-subject activation variability in the posterior cingulate, supramarginal gyrus, and inferior frontal gyrus (Bonferroni FWE-corrected ps<0.05)—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.

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Keywords

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Introduction

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 we attend to, interpret, and respond to socio-emotional 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 children as young as infants[10–12], it is critical that we identify how social anxiety is associated with emotion processing across development. Importantly, understanding both mean differences in processing as well as neurological heterogeneity across individuals with social anxiety would provide important insight into the pathophysiology of social anxiety. Here, we use a large sample of fMRI collected during movie-watching to examine complex emotion processing differences associated with social anxiety in youth. Specifically, we examine both central tendency (i.e., how social anxiety is generally associated with emotion processing) as well as heterogeneity (i.e., 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) find that individuals with social anxiety are quicker to attend to angry or fearful faces than neutral, 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, 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 high in social anxiety could be associated with differences the brain networks that support these functions.

The neurological basis for these differences in real-world socio-emotional processing are not yet well-understood. The work above suggests differences in both the early and 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]. Previous work using context-poor emotional stimuli (such as

emotional faces) has found limited differences in brain activation associated with social anxiety symptoms, however. 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 youth studies of social anxiety 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 (e.g., 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 to what degree this pattern of results would be present for less controlled, more naturalistic stimuli, however. 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 are 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–i.e., 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 social anxiety symptom development. The degree of similarity of neural activation across individuals with social anxiety has not yet been examined, thus it is unclear how individual differences in neural function matters for treating social anxiety symptoms. Directly assessing the degree of heterogeneity in social processing in children high in 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 uses video stimuli to examine contextualized socio-emotional processing associated with social anxiety symptoms in youth. We have three aims: 1) identify what patterns of activation to emotion stimuli are associated with social anxiety symptoms with respect to mean and inter-subject variability; 2) characterize the specific scenes that elicit these associations; and 3) test if the results of these analyses differ as a function of developmental stage. To accomplish these aims, we leverage a large dataset of fMRI data collected while children watch emotional video clips. We use multivariate methods and split our data into discovery and replication sets to maximize reproducibility. Our analyses are designed to characterize both patterns of activation that are systematically associated with

social anxiety symptoms at the mean level (mean tendency; regression-based) as well as characterizing the degree of heterogeneity in activation responses associated with social anxiety symptoms (sample heterogeneity; similarity-based). Based on previous literature and emotion theory, we predict variation in activation to negative emotions in attentional, default mode, and primary sensory regions of the brain to relate to social anxiety symptoms. We expect 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 do not predict large differences in associations between brain activation and social anxiety symptoms in older versus 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 the supplement (Supplement 1, available online).

Sample and Study information

These analyses included data from 740 5-to-15-year-old participants from the Healthy Brain Network Biobank[37] previously analyzed to examine developmental differences in emotion processing[36]. Briefly, children and young adults were recruited across four 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 higher average motion, lower depression scores, lower self-reported social anxiety scores, and fewer participants were 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)[38] is a 41-item questionnaire that was completed by parents for their children (all children) and by children for themselves (ages 8 and up only). The social anxiety subscale score was used for further analysis, which has a possible score range of 0–14, with higher scores indicating greater symptom severity. Parent and self-reported scores were modestly correlated (Spearman r=0.28, p<0.001). Distributions of scores across age are shown in Figure S7, available online.

Depression Symptoms: The Mood and Feelings Questionnaire (MFQ)[39] is a 34-item questionnaire completed by parents for their children (all participants) and by children for themselves (ages 8 and up only). Parent and self-reported scores were modestly correlated (Spearman r=0.25, p<0.001). As expected, social anxiety and depression scores were

correlated (parent-report r=0.25, self-report r=0.42, ps<0.001), as were generalized anxiety and depression scores (parent-report r=0.50, self-report r=0.57, ps<0.001). We used total scores as a covariate in further analyses, matching social anxiety symptom informant.

Neural Activation to Emotional Videos

Children watched a ten-minute segment of *Despicable Me* and the 3-minute 20-second Pixar short called *The Present* during fMRI 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[40] to create a timeseries of each broad emotion (positive, negative) and specific emotions (fearful, angry, sad, happy, excited), as well as non-emotional video features. While specific emotions (e.g., angry, fearful, sad) are also captured in the broad emotion categories (e.g., negative), we examined them separately for better comparison with the broader literature that used either an emotion category approach (angry, fearful) or a 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 timeseries regressors to estimate activation for negative, angry, and fearful content in each video. Given research showing that anxiety is associated with sensory sensitivity[41–43], we also estimated activation to low-level brightness and loudness. For a more detailed description of this method, please see Supplement 1, available online. Traces for select video content over time and scene descriptions are in Figures 1 and S1 while full features are shown in Figure S2, available online. Video feature analysis results are shown in Figures S3 and S4, available online. Non-emotional 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 1–2 samples per activation map depending on if there was usable data 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 twenty models were run (5 activation map categories [negative, angry, fearful, brightness, loudness] x 2 SVR kernel models [linear, nonlinear] x 2 social anxiety score sources [parent-report, self-report]). For a more detailed description of this method, please see Supplement 1, available online.

Inter-subject 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 inter-subject similarity in activation across children higher in social anxiety as compared to low symptom children. To accomplish this, we employed inter-subject representation similarity analysis (IS-RSA)[44] to test three 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 residualized before analysis (regressing out age, sex, mean motion, and depression symptoms). Neural similarity was computed as parcel-wise inter-subject correlation (ISC). IS-RSA for each parcel was computed as the correlation between ISC and symptom similarity values. P-values were assigned by permuting the behavioral similarity scores to generate a null distribution of 10,000 values. Parcels were considered significant at $\alpha<0.05$ after Bonferroni-style family-wise error (FWE) correction. These procedures were repeated across videos and samples. Boot-strapped statistical distributions for each model were tested against each other for each significant parcel to determine the best fitting and replicable model. For a more detailed description of this method, please see Supplement 1, available online. For the younger and older subsample analysis, we also statistically compared the coefficient distributions between the samples using a paired t-test.

IS-RSA were also repeated covarying Attention Deficit Hyperactive Disorder (ADHD) symptom scores due 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 S5, 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 S6, 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 movie to parse what content evoked synchronous or heterogeneous responses. To accomplish this, we computed pair-wise inter-subject phase synchrony (ISPS) for the children with each 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, 21–30% met criteria for lifetime social anxiety disorder and 44–56% 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 timepoint in the series to identify when in each video the top and bottom 20% of the sample significantly differed in ISPS distributions, and p-values were assigned using a subject-wise 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 timeseries t-test analysis were next analyzed quantitatively and qualitatively to determine what kind of content induced similar patterns of activation in the highest or lowest symptom children as appropriate for the model identified in the IS-RSA.

Motion

We have included an extensive analysis of motion in relation to each analysis approach, video features, and psychiatric symptoms 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 ($rs<0.06$, $ps>0.104$). Full model statistics are shown in Table S1, available online. These results demonstrate a lack of mean differences in activation between low and high social anxiety children, failing to replicate previous work using smaller samples, univariate statistics, and context-poor stimuli.

Children higher in social anxiety symptoms have more heterogeneous activation patterns to emotional movies than children lower in symptoms

Using inter-subject representational similarity analysis, we found that increased parent-reported social anxiety symptoms were associated with greater inter-subject variability in activation of 10 regions of the brain spanning the posterior cingulate, supramarginal gyrus, 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 fronto-parietal networks. Only one parcel in the post-central gyrus best fit the consistent-high model (more consistent activation across higher symptom children). 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 two parcels replicated across videos and samples. One parcel was the right lateral occipital lobe in the visual network and the other was of 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* overlap: 33%; self-report overlap: *Despicable Me*: 33%, *The Present* overlap: 14%) and between movies (parent-report overlap: 25%; self-report overlap: 8%), but all overlaps were greater than chance ($I^2>19.67$, $ps<0.001$). 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-year-olds) or older (10–15-year-olds) 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=0.252) and that there was a stronger Variable-High effect in the older children for The Present (t=2.70, p=0.009). Overall, these results show that higher symptoms are associated with more inter-subject heterogeneity in activation during naturalistic emotion processing in regions associated with attentional and higher order sensory processing both for younger children and older youth.

Scenes with higher sensory intensity evoke heterogeneous activation among high symptom children

To infer what combination of stimuli elicits greater inter-subject activation heterogeneity among children with higher social anxiety symptoms, we compared the inter-subject phase synchrony distributions between the lowest and highest symptom children for each video and each information (self or parent) across the parcels that best fit the variable-high model. Across informants, there was greater inter-subject activation variability among high symptom children than among low symptom children for approximately half of *Despicable Me* (46% of the runtime for self-report, 53% for parent-report), which included scenes that were on average brighter and more vibrant with less emotional content (Figures 3 and 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, more vibrant, had more motion, and had fewer characters in both age groups (Figure 3). There was greater inter-subject synchrony in low parent-reported social anxiety symptom children as compared to higher symptom children in five scenes in *The Present.* No scenes in *The Present* were identified for self-reported social anxiety. Results are in Figures S11 and S12, available online.

Discussion

This project sought to characterize the association between social anxiety symptoms and activation to emotional videos in a large sample of 5-to-15-year-old children. We found no mean differences in activation patterns between children high and low in 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 higher in social anxiety symptoms compared to children lower in 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 higher symptom children relative to lower symptom children. 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 this pattern of greater heterogeneity is unique to social 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 high symptom children was observed across age groups, as well as a similar pattern of higher sensory intensity scenes associated with significant differences in inter-subject 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 inter-subject synchrony in low versus high symptom children.

We found that scenes associated with greater inter-subject variability in the higher symptom children had higher sensory intensity. While limited, there is previous research finding over-sensitivity 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 finding differences in activation or behavior on the basis of emotional content are actually detecting differences in saliency and sensory processing present in high social anxiety individuals. 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 reinforced 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 support 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[45]. 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[46,47], 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 high in social anxiety who live in a noisy household, for example, may be able to acclimate to louder movies scenes similarly to their unaffected peers but not to sudden shifts in brightness. Similarly, socially anxious children who have experienced trauma may exhibit overactive automatic processing that is further heightened following negative emotion cues, resulting in different activation patterns in 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 high social anxiety children we observed emerges.

This study has several strengths which innovate 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 that are important to consider. 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 questionnaires for our measure of social anxiety symptoms, which are 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 cartoons can change music and color palettes to evoke certain moods. Nonetheless, examining differences in movie-watching lends insight to more naturalistic socio-emotional 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 *Despicable Me* was a 10-minute clip) or because *The Present* is less dynamic in terms of brightness, loudness, and motion as compared to *Despicable Me*. Future work should examine activation to several video clips with varied sensory and social content to draw broader conclusions.

In summary, here we found evidence that increased social anxiety symptoms are associated with greater variability in activation during emotionally dynamic videos in children. The specific regions that show this pattern varied by age and informant. Intriguingly, increased sensory intensity on the screen was associated with greater inter-subject activation variability in the highest symptom children as compared to the lowest symptom children, but presence

of negative affect was not. These results provide insight to the complex relationship between social anxiety symptoms and real-world socio-emotional processing. Further work is needed to connect developmentally-sensitive objective measures of social anxiety with naturalistic emotion processing in order to better understand how these symptoms affect child development and functioning.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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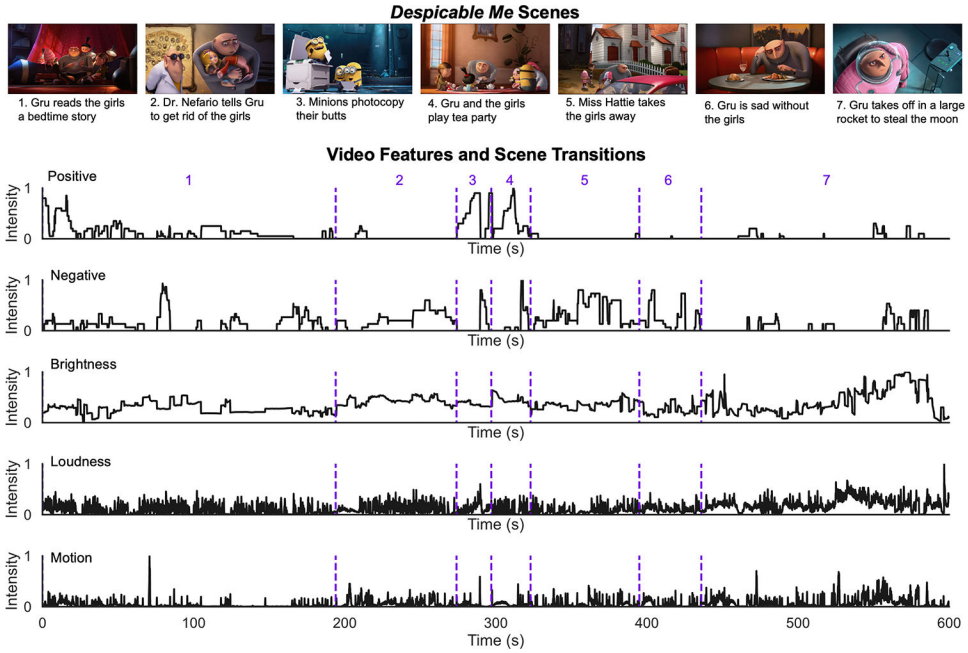

Figure 1:

Scene descriptions and transitions in *Despicable Me*. Select video features are plotted with vertical dashed lines indicating scene transitions.

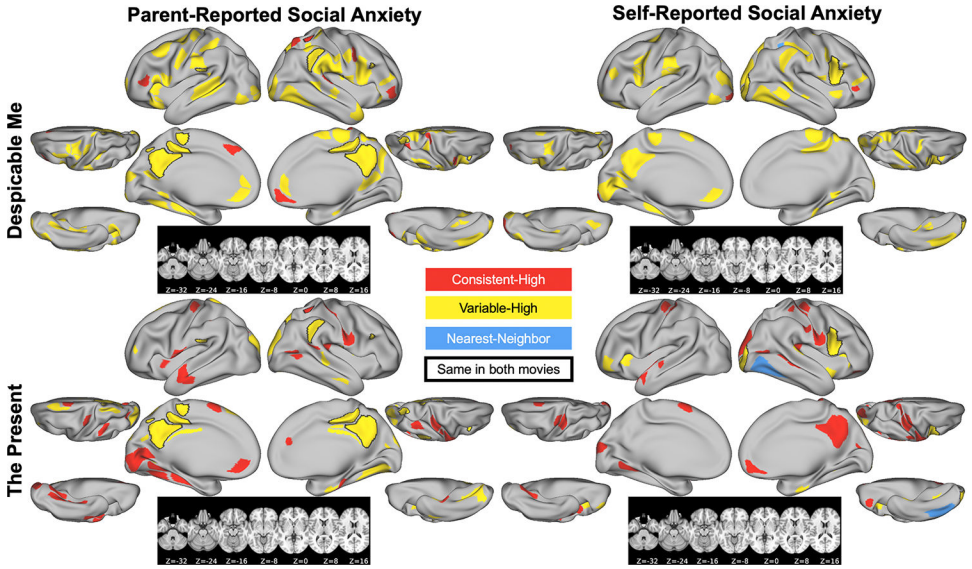

Figure 2:

Results from the inter-subject representational similarity analysis (IS-RSA) model fit comparisons. Results for parent-reported social anxiety are shown on the left and for self-reported social anxiety on the right. The dominant model was Variable-High, 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.

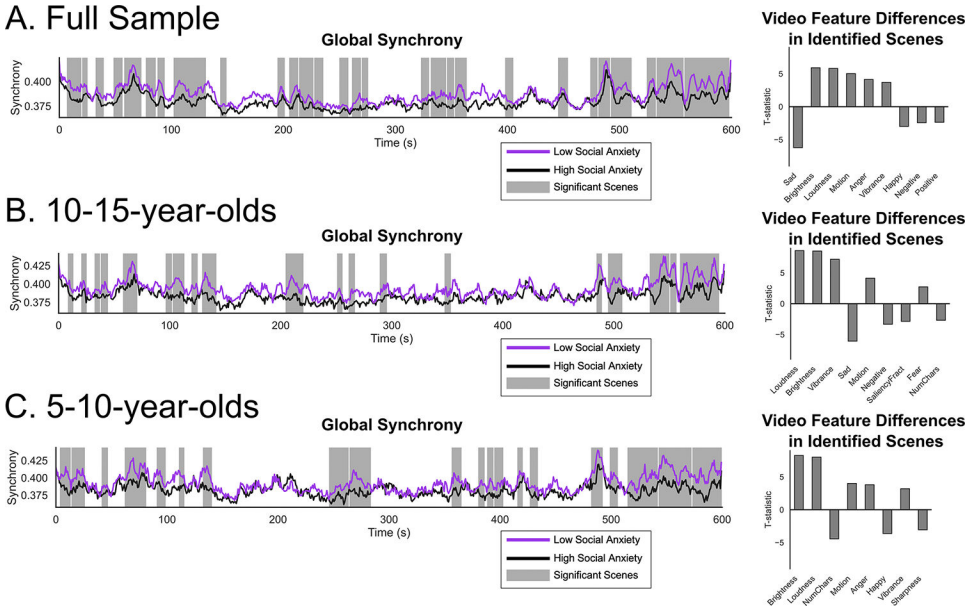

Figure 3:

Dynamic similarity results for *Despicable Me.* We compare children highest (top 20%) and lowest (bottom 20%) in parent-reported social anxiety symptoms. **Line plots**: The shaded portion of each timeseries indicates the video segment during which between-subject activation similarity significantly differed between low and high symptom children (p<0.05 for at least 4 seconds and in both samples). **Video Feature Analysis**: Bar plot with video features significantly different in the identified scenes compared to the rest of the video (Benjamini-Hochberg FDR-corrected p<0.05).

Table 1:

Sample demographic and clinical data summary. Puberty scores were obtained using the Peterson puberty index[48]; ADHD symptoms from the Strengths and Weaknesses of Attention-Deficit/Hyperactivity Disorder (Symptoms and Normal Behavior questionnaire[49]; and diagnoses were obtained from clinical consensus based on the Kiddie Schedule for Affective Disorders and Schizophrenia[50] combined with observations and questionnaire responses. ADHD = Attention-Deficit/Hyperactivity Disorder.

	Low-Motion Data (N=740)					
Characteristic	**Discovery/Training (n=386)**		**Replication/Testing (n=354)**		***t, X²*, *or U***	**p-value**
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)	X^2=0.83	.361
Right-handed	293	(76)	258	(73)	X^2=0.89	.346
Race	**n**	**(%)**	**n**	**(%)**	X^2=10.19	.178
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	**n**	**(%)**	**n**	**(%)**	X^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	**n**	**(%)**	**n**	**(%)**	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)		

	Low-Motion Data (N=740)					
Characteristic	**Discovery/Training (n=386)**		**Replication/Testing (n=354)**		***t, X²*, *or U***	**p-value**
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	(8.0)	t=2.01	.045
Parent-reported ADHD symptoms	0.4	(0.9)	0.3	(1.0)	t=1.45	.149
Clinical Diagnoses	**n**	**(%)**	**n**	**(%)**		
Depressive	35	(14)	33	(13)	X^2=0.18	.672
Anxiety	119	(49)	135	(54)	X^2=1.05	.306
Bipolar	2	(1)	0	(0)	X^2=2.08	.149
Disruptive	51	(21)	40	(16)	X^2=2.16	.142
Elimination	35	(14)	31	(12)	X^2=0.47	.491
Eating	3	(1)	3	(1)	X^2=0.00	.964
Learning	66	(27)	98	(39)	X^2=7.69	.006
Attention-Deficit/Hyperactive	163	(67)	163	(65)	X^2=0.32	.571
Autism	45	(19)	45	(18)	X^2=0.06	.848
Obsessive Compulsive	19	(8)	22	(9)	X^2=0.13	.713
Trauma or Stress	12	(5)	19	(8)	X^2=1.43	.232
No Diagnosis	3	(1)	1	(0)	X^2=1.08	.298
Missing or incomplete	144	(37)	103	(29)	X^2=5.60	.018