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Temperamental Shyness, Frontal EEG Theta/Beta Ratio, and Social Anxiety in Children

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The authors examined how children's frontal electroencephalogram (EEG) theta/beta ratio—an index of neurocognitive control—changed from baseline to a social stressor, and whether these EEG changes moderated the relation between temperament and anxiety. Children (N = 152; M_{age} = 7.82 years, 52% male, 81% White) had their EEG recorded during a baseline and speech anticipation condition. Children's frontal theta/beta ratio decreased from baseline to speech anticipation, and this baseline-to-task change moderated the relation between temperamental shyness and social anxiety. Temperamental shyness was related to higher state and trait social anxiety only among children with large baseline-to-task decreases in theta/beta ratio. Findings are consistent with theoretical models hypothesizing that temperamentally shy children with heightened neurocognitive control may be at greater risk for anxiety.

Temperamental shyness is characterized by wariness and fear in response to social novelty and situations of perceived social evaluation (Kagan, Reznick, & Snidman, 1987). Shyness is thought to be rooted in early behavioral inhibition (BI), a biologically based temperament characterized by fear to novelty more broadly encompassing both social and nonsocial stimuli (García-Coll, Kagan, & Reznick, 1984). Typically, BI is assessed and viewed as a temperamental trait in infancy and toddlerhood (Fox, Henderson, Rubin, Calkins, & Schmidt, 2001), whereas temperamental shyness is a conceptually similar trait later in childhood that is specific to social contexts (Poole, Tang, & Schmidt, 2018). Previous work has found that BI and temperamental shyness are concurrently and prospectively related to internalizing difficulties, though a robust finding is that these temperamental styles are related to an increased risk for social anxiety in particular (Chronis-Tuscano et al., 2009; Clauss & Blackford, 2012; Hirshfeld-Becker et al., 2007; Lahat, Lamm, et al., 2014; Sandstrom, Uher, & Pavlova, 2020; Schwartz, Snidman, & Kagan, 1999; Tang et al., 2017; Tsui, Lahat, & Schmidt, 2017). Despite the direct relation between temperamental shyness and risk for social anxiety, not all shy children manifest these psychological difficulties. Accordingly, there has been interest in attempting to identify risk or resilience factors that may alter the temperamental shyness-anxiety relation. One factor that may be particularly influential on this association is a child's level of cognitive control.

Cognitive control encompasses the effortful and voluntary processes that are dependent on neural networks responsible for executive function (Posner & Rothbart, 2007). Although higher levels of cognitive control are typically viewed as adaptive, it has been theorized that individual differences in controlled cognitive processes have differential influences on a child's developmental outcomes depending on a child's temperament (Buzzell, Troller-Renfree, Morales, & Fox, 2018; Henderson, Pine, & Fox, 2015; Henderson & Wilson, 2017). Specifically, according to the risk potentiation model of control (see Henderson et al., 2015), children with reactive temperaments (e.g., temperamental inhibition/shyness), who also have heightened cognitive control processes, are at greater risk for anxiety (Derryberry & Rothbart, 1997; Henderson & Wilson,

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2017; Henderson et al., 2015). It is thought that these children may spend greater time monitoring their social environment, which may result in limited flexibility to engage with the environment, and the perception that social situations are distressing (Derryberry & Rothbart, 1997; Henderson & Wilson, 2017; Henderson et al., 2015). Collectively, this may result in an "over" controlled style of processing, a behavioral style marked by rigidity, and may confer risk for higher levels of social anxiety.

A series of studies have provided empirical support for the risk potentiation model of control. For example, toddlers with a trajectory of high parent-reported shyness from age 2 to 5 who also had high levels of inhibitory control (observer-rated during a snack delay task and parent-reported composite) displayed the highest number of observed socially anxious behaviors with unfamiliar peers at age 5 (Brooker, Kiel, & Buss, 2016). Additional work found that BI in toddlerhood was predictive of parent-reported anxiety symptoms in preschoolers with high levels of inhibitory control (assessed using laboratory Stroop tasks; White, McDermott, Degnan, Henderson, & Fox, 2011). A similar pattern of findings was recently reported such that behaviorally inhibited toddlers who exhibited increases in inhibitory control (assessed using a Go/NoGo task) across childhood had heightened symptoms of social anxiety at age 12 (Troller-Renfree et al., 2019). Among preschoolers, temperamental shyness was negatively related to concurrent teacher-reported prosocial behavior and popularity with peers only among children with relatively high levels of parent-reported inhibitory control (Sette, Hipson, Zava, Baumgartner, & Coplan, 2018). Likewise, a recent study with preschoolers reported that temperamental shyness was related to lower observed social engagement and less social support seeking among children with high levels of parent-reported attentional control (Hassan, Poole, & Schmidt, 2020). A longitudinal study also found that a combination of high temperamental shyness and high levels of inhibitory control (assessed using a Go/NoGo task) during preschool was predictive of higher teacher-reported social anxiety and lower social initiative at age 8 (Thorell, Bohlin, & Rydell, 2004).

Despite the fact that controlled cognitive processes are mediated by neural networks responsible for executive function (Posner & Rothbart, 2007), relatively less work has examined neurobiological indices of cognitive control as moderators on the shyness-anxiety relation. Henderson (2010) found that child-reported temperamental shyness was concurrently related to higher levels of social anxiety and a negative attribution style among children who exhibited exaggerated neurocognitive control as assessed by the N2 event-related potential (ERP) in response to a laboratory inhibitory control task. A longitudinally followed sample replicated this finding and found that a combination of high BI in toddlerhood and an enhanced N2 ERP during an inhibitory control task at age 7 was predictive of higher observed social withdrawal and lower social assertiveness (Lahat, Walker, et al., 2014) and greater observed social reticence (Lamm et al., 2014).

An additional electrophysiological marker of cognitive control is the frontal electroencephalogram (EEG) theta/beta ratio (Angelidis, Hagenaars, van Son, van der Does, & Putman, 2018; Angelidis, van der Does, Schakel, & Putman, 2016; Putman, Verkuil, Arias-Garcia, Pantazi, & van Schie, 2014; van Son et al., 2019). A higher theta/beta ratio score reflects a relatively greater proportion of slow wave (i.e., theta) relative to fast wave (i.e., beta) activity, which may be indicative of relatively less voluntary, top-down control processes in the cortical networks over the bottom-up processes in subcortical networks (Angelidis et al., 2016, 2018; Putman, van Peer, Maimari, & van der Werff, 2010; Putman et al., 2014; Schutter & Van Honk, 2005). Thus, a lower theta/beta ratio is presumed to reflect greater cognitive control.

A body of empirical work supports the use of frontal EEG theta/beta ratio as an index of an individual's level of cognitive control. In healthy adults, a lower baseline frontal theta/beta ratio was related to greater inhibitory control in a Go/NoGo task and self-reported attentional control (Putman et al., 2010, 2014). In a separate study, baseline theta/beta ratio demonstrated test-retest reliability across 1 week, and a lower baseline theta/beta ratio was concurrently and prospectively related to higher self-reported attentional control 1 week later (Angelidis et al., 2016). An extensive body of work also has noted a higher baseline theta/beta ratio in clinical samples of children with attention deficit hyperactivity disorder (see Arns, Conners, & Kraemer, 2013, for a review), a disorder characterized by deficits in cognitive control. Relatively less work has examined frontal theta/beta ratio in typically developing children. In one study of typically developing 3- to 9-year-old children, a lower baseline theta/-beta ratio was related to higher levels of executive function (Perone, Palanisamy, & Carlson, 2018). Likewise, Cuevas, Wang, and Bell (2020) recently reported that a lower baseline theta/beta ratio was correlated with higher executive function among typically developing 8-month-old infants.

In the studies reviewed earlier, resting state (i.e., baseline) patterns of EEG were analyzed, which is thought to reflect an individual's trait-like pattern of responding that is relatively stable (Reznik & Allen, 2018). Relatively less work, however, has examined changes in an individual's frontal theta/-beta ratio during manipulations in the laboratory. An exception is a recent study by van Son et al., (2019) that examined healthy adult females' frontal theta/beta ratio while they were focussing on their breathing compared to when they were mind wandering. The authors of that study found that frontal theta/beta ratio was higher while participants were mind wandering relative to when they were engaging in focussed attention on their breathing (van Son et al., 2019). Because mind wandering is conceptualized as a state of reduced cognitive control (see van Son et al., 2019), the findings provide support that higher levels of theta/beta ratio may be indicative of reduced cognitive control. This study also illustrates that frontal theta/beta ratio may manifest changes in response to task-related neurocognitive demands.

Although previous work to date has been informative in understanding the role of cognitive control on the link between temperamental shyness and internalizing problems, the majority of existing studies have measured cognitive control using parent-report or laboratory tasks in nonaffective contexts. Given that temperamental shyness and social anxiety are particularly salient in *social* contexts, we hypothesized that neurocognitive control during socially relevant laboratory tasks would serve as a risk factor for understanding the shyness-social anxiety relation. One method to assess neurocognitive control in response to a social challenge is to assess an individual's change in theta/beta ratio from baseline to a social stressor, as this may be reflective of his or her efforts to regulate a stressful state. Although we do not know of any work that has specifically examined changes in EEG theta/beta ratio from baseline to a social stressor, work using additional EEG-based measures has illustrated that frontal brain activity patterns are sensitive to change during social stressors such as preparation of a speech (e.g., Cole, Zapp, Nelson, & Pérez-Edgar, 2012; Davidson, Marshall, Tomarken, & Henriques, 2000; Miskovic et al., 2010; Schmidt, Fox, Schulkin, & Gold, 1999).

In this study, we wished to interface two relatively disparate lines of research by examining changes in children's frontal EEG theta/beta ratio from baseline to a social stress task (i.e., anticipation of delivering a speech) to index children's neurocognitive control during a socially relevant context. To our knowledge, this is the first examination to track changes in frontal theta/beta ratio in response to an affective challenge in the laboratory. Although psychophysiology measured across baseline and laboratory tasks may be correlated, there is individual variability in the relative level of stability or change (i.e., increase or decrease) in the physiological measure under investigation. Accordingly, we also examined whether individual differences in the magnitude of frontal theta/beta ratio change to the social stressor moderated the relation between children's temperamental shyness and their levels of social anxiety.

We focussed specifically on typically developing children in middle childhood for a number of reasons. First, around age 7 or 8, children have developed a sense of self, an understanding of social-evaluative concerns from peers, and there is an increase in self-conscious emotional development (Crozier & Burnham, 1990; Harter, 1986; Lagattuta & Thompson, 2007). Second, by middle childhood, children have the capacity to process an impending social stressor (Schmidt et al., 1999) and are also more aware of their internal affective states, allowing for reliable examination of their subjective levels of social anxiety. Finally, this age corresponds to a developmental rise of social fears, typically preceding the onset of clinical levels of social anxiety which generally occurs during late childhood to early adolescence (Knappe, Sasagawa, & Creswell, 2015). Given that these developmental factors become salient in situations where a child may be observed, assessed, and evaluated by peers, in this study, we had children engage in a task where they were anticipating delivering a speech to unfamiliar peers in front of a video camera, in order to elicit social evaluative and self-presentation concerns.

Based on previous theoretical (Henderson & Wilson, 2017; Henderson et al., 2015) and empirical (Hassan et al., 2020; Henderson, 2010; Sette et al., 2018; Thorell et al., 2004; Troller-Renfree et al., 2019; White, McDermott, et al., 2011) work, we predicted that temperamental shyness would be related to an increased risk for social anxiety among children who showed heightened neurocognitive control (i.e., large decreases in frontal theta/beta ratio) during the social stress induction. In order to provide convergent evidence, children's social anxiety was assessed at both a *state* level, reported in response to an impending speech task, as well as at a *trait* level which assessed their dispositional anxiety more broadly across contexts. As well, in order to provide discriminant evidence, we examined whether our pattern of results was specific to *social* anxiety by performing specificity analyses in which trait generalized anxiety was included as a dependent measure. We expected that our pattern of findings would be significant across both state and trait measures of social anxiety, and that there would be specificity to social anxiety and not generalized anxiety (Hirshfeld-Becker et al., 2007; Schwartz et al., 1999).

Method

Sample

Participants included 152 typically developing children (73 girls; M_{age} = 7.82 years, SD = 0.44) and their caregivers (M_{age} = 39.95 years, SD = 4.27; 90% mothers, 10% fathers). Children were primarily White (81.6%), followed by Mixed Race (9.9%), Asian (3.9%), African American (2.6%), and Latin American (2%), and primarily from middle to upper socioeconomic class families as indicated by total household income in Canadian dollars (< $60,000 = 14.5%; $60,001–$100,000 = 19.7%; > $100,000 = 65.8%).

Children were recruited from a database containing the names and contact information of infants whose parents consented for their infant's inclusion in the McMaster Child Database if they were interested in participating in future developmental research studies conducted in the Department of Psychology, Neuroscience & Behaviour at McMaster University. The children were born at hospitals located in Southern Ontario, Canada. Data collection occurred between the years 2018 and 2019.

Procedure

Children and their caregivers visited the Child Emotion Laboratory at McMaster University. After obtaining written informed consent from the parent and the child, the child was fitted with an EEG cap and an ambulatory electrocardiograph (ECG) monitor. Children were then brought to the psychophysiological recording room where EEG and ECG were recorded during baseline and speech anticipation periods. The ECG data were collected as part of a larger study examining psychological and psychophysiological correlates of socioemotional development and are not included in the analyses below (See Poole & Schmidt, 2021).

While the parent completed electronic questionnaires related to the child's socioemotional development, the child and the researcher completed additional activities. Of particular interest to this study was the child's responses related to their levels of anxiety, assessed via the Screen for Child Anxiety Related Disorders (SCARED)–Child Version (described in the next section; Birmaher et al., 1997), which took approximately 5 min to complete. As part of the larger study, children also provided responses to additional questionnaires related to their self-esteem, social competence, self-consciousness, and perception of emotional faces, and interacted with an unfamiliar member of the research team (not reported here). The parent could watch the child participating in these activities on a muted, closed-circuit computer monitor, of which the child was aware. The study visit took approximately 75–90 min to complete. The family received a $20 gift card, and children received a *Junior Scientist* certificate to compensate them for their participation. All procedures were approved by the McMaster University Research Ethics Board.

EEG Data Collection and Reduction

Baseline and Speech Anticipation Recording Periods

EEG activity was first recorded during a 2-min baseline period (alternating between 1-min eyes open and 1-min eyes closed) while the child viewed an image on a computer screen depicting eyes that were open and closed. Following the collection of baseline EEG, 2 min of EEG were collected during the social stress induction in which the child had his/her eyes open. The researcher was present during both the baseline and speech anticipation periods. For the speech anticipation period, the researcher gave the child the following instructions: *The next activity you will do is give a speech to other children about your last birthday. We will video tape this presentation so that other boys and girls can see you and hear all about you! Before we videotape your speech, I want you to think about your last birthday without talking so you know what you want to say in your speech for the other children to see. You will have 2 min to prepare this speech in your head. I will tell you when your time is all up!*

In order to increase the level of stress during the anticipation period, the experimenter gave the child two prompts. The first prompt occurred after 45 s: *Remember that other boys and girls are going to see you and hear your speech, so try to think really hard about what you want to say!*, and the second prompt occurred after 90 s: *Thirty more seconds and then it's time for you to give your speech!*. A similar social stress induction task has been used in other studies with children (Schmidt et al., 1999) and adults (Miskovic et al., 2010).

EEG activity was continuously recorded using a 128-channel geodesic sensor net (Electrical Geodesics Inc., Eugene, OR). Data from each channel were digitized at a 250 Hz sampling rate. EEG channels were collected with reference to Cz and re-referenced offline to the average of all electrodes (Junghöfer, Elbert, Tucker, & Braun, 1999). All data preparation and processing were conducted offline using Brain Vision Analyzer (Brain Products GmbH, Gilching, Germany). Data were filtered with a high-pass frequency of 0.1 Hz, a low-pass frequency of 30 Hz, and a 60 Hz notch filter. Data were visually inspected first to remove electrodes with high impedance or noisy signal and were interpolated by surrounding channels. Ocular artifacts from eye blinks and horizontal eye movements were corrected using independent component analysis. Data were segmented into 1-s epochs using 50% overlap and baseline corrected using the entire segment. Epochs exceeding $\pm$ 120 μV, a voltage step of more than 75 μV between sample points, or a maximum voltage difference of less than 0.50 μV within any 100-ms interval were marked as artifacts and automatically removed. Data were also visually inspected for any remaining artifacts. EEG power was computed using a Fast-Fourier Transformation with full spectrum and a Hamming window length of 50%.

The mean number of useable segments was 160 (SD = 67, range = 22–261) for the baseline condition and 149 (SD = 64, range = 20–249) for the speech anticipation condition. The number of segments during baseline or speech condition was not significantly correlated with child age, familial income, children's temperamental shyness, state social anxiety, or trait social anxiety, rs < .17, ps > .05, but girls had more useable segments relative to boys for the baseline condition, $t(143) = 2.81$, $p = .01$.

Regional absolute EEG power (in μV^2) was derived in the theta (4–7 Hz) and beta (14–20 Hz) frequency bands for each electrode of interest (i.e., F3, Fz, F4). Locations of the electrode sites of interest corresponded to the 10–20 system of the International Federation (Jasper, 1958). Because the eyes-open and eyes-closed conditions were highly correlated across electrodes, they were combined to derive an aggregate measure of baseline EEG power separately for each electrode site (F3 theta: $r = .99$, $p < .001$; F3 beta: $r = .90$, $p < .001$; Fz theta: $r = .99$, $p < .001$; Fz beta: $r = .94$, $p < .001$; F4 theta: $r = .94$, $p < .001$; F4 beta: $r = .92$, $p < .001$). We then created a variable to capture the average of the frontal region (average of F3, Fz, and F4) for the baseline and speech anticipation periods separately. We were interested in the frontal electrodes based on previous research finding the frontal region being particularly relevant to cognitive control (Angelidis et al., 2016, 2018; Putman et al., 2010). The frontal theta/beta ratio was calculated by dividing the frontal theta by frontal beta power separately for the baseline and speech anticipation periods. We were interested in the change in children's frontal theta/beta ratio from baseline to the social stressor, and we therefore computed a frontal theta/beta ratio change score by subtracting the baseline frontal theta/beta ratio score from the speech anticipation frontal theta/beta ratio. On this metric, lower (i.e., more negative) scores reflect larger decreases in frontal theta/beta ratio (i.e., greater neurocognitive control) from baseline to social stress induction.

Children's Temperamental Shyness

Primary caregivers completed the shyness subscale from the Colorado Child Temperament Inventory (Rowe & Plomin, 1977). Five items comprise the shyness subscale, each of which is rated on a 5-point Likert scale ranging from 1 = *strongly disagree* to 5 = *strongly agree*. Example items from the shyness subscale include: "Child tends to be shy" and "Child takes a long time to warm up to strangers". The shyness subscale demonstrated good internal consistency (α = .84).

Children's Anxiety

State Social Anxiety

Children reported on their state nervousness immediately following the baseline condition and immediately following the speech anticipation period using a "*Feelings Thermometer*". The researcher first showed the child the *Feelings Thermometer* and explained that it measures how the child is feeling, with 0 reflecting that the child is not at all nervous, and 10 reflecting that the child is extremely nervous. The *Feelings Thermometer* also contained cartoon faces depicting increasing levels of nervousness as a visual representation across the scale. The child reported on his/her nervousness by pointing to a number between 0 and 10. The child's subjective nervousness to the speech anticipation period was operationalized as his/her state social anxiety.

Trait Social Anxiety and Generalized Anxiety

Children responded to items from the *SCARED–Child Version* (Birmaher et al., 1997), which is a widely used measure of childhood anxiety designed to measure symptoms consistent with anxiety disorders outlined in the Diagnostic and Statistical Manual of Mental Disorders, 4th ed. Of particular interest for this study was the seven-item social anxiety and the nine-item generalized anxiety subscales. A sample item from the social anxiety subscale is: "I feel nervous when I am with other children or adults and I have to do something while they watch me", and a sample item from the generalized anxiety subscale is: "I am a worrier". The researcher read aloud each item to the child and he/she responded by pointing to his/her response on a pictorial response sheet, ranging from 0 = *not true* to 2 = *often true*. The child received initial training on using this response format. The social anxiety (α = .72) and generalized anxiety (α = .70) subscales demonstrated acceptable internal consistency.

Missing Data

There were missing baseline EEG data due to thick hair (n = 4), child refusal to wear EEG cap (n = 1), equipment failure (n = 2), excessive artifact (< 20 segments of useable data; n = 10), and extreme values for theta power (3 $SD \pm$ mean; n = 3), resulting in 132 children with baseline EEG data. For the speech anticipation period, there were missing EEG data due to thick hair (n = 4), child refusal to wear EEG cap (n = 1), equipment failure (n = 2), and excessive artifact (<20 segments of useable data; n = 11), resulting in 134 children with speech anticipation EEG data. Children with missing EEG data did not significantly differ from children with complete data on child age, familial income, children's temperamental shyness, state social anxiety, or trait social anxiety, ts < 1.36, ps > .18, or child sex, χ^2 = 0.06, p = .80.

One child was missing self-reported subjective nervousness to speech anticipation, and one child was missing self-reported trait anxiety. The subjective nervousness measure during the baseline condition was added to the study part way through data collection, resulting in 86 children having baseline subjective nervousness data. Children with missing subjective baseline data did not significantly differ from those with baseline data on age, familial income, temperamental shyness, trait social anxiety, ps < 1.79, ps > .08, or sex, χ^2 = 0.31, p = .58, but children with missing baseline data self-reported greater nervousness during the speech anticipation period, $t(149)$ = 2.87, p = .005.

Little's missing completely at random test revealed the data were missing at random, χ^2 = 36.81, p = .39. Multiple imputation was used to impute missing data across 40 imputations to avoid the biased parameter estimates that can occur with pairwise or listwise deletion (Schafer & Graham, 2002; White, Royston, et al., 2011). Findings using pairwise deletion produced statistically similar results.

Statistical Analyses

We used multiple linear regressions to examine whether change in frontal theta/beta ratio from baseline to speech anticipation moderated the relation between children's temperamental shyness and anxiety. In the first step, we entered continuous scores of temperamental shyness and frontal theta/beta ratio change as main effects. In the second step, we entered an interaction term that was the cross-product of continuous temperamental shyness and frontal theta/beta ratio change. In the final step, we entered child sex, age, and familial income as covariates to provide adjusted results. Significant interactions were probed by examining the influence of temperamental shyness on anxiety for children with large decreases in theta/beta ratio (1 SD below the mean), average decreases in theta/beta ratio (mean), and increases in theta/beta ratio (1 SD above the mean). All statistical analyses were performed using SPSS Version 24.0 (IBM Corp, Armonk, NY, USA).

Results

Descriptive Statistics

Descriptive statistics are presented in Table 1. Children's state social anxiety was modestly correlated with trait social anxiety, r = .18, p = .03, and generalized anxiety, r = .16, p = .05. Children's trait social and generalized anxiety were also positively related, r = .37, p < .001. Girls reported higher levels of trait social anxiety relative to boys, $t(149)$ = 2.67, p = .01. State social anxiety was inversely correlated with familial income, r = −.23, p = .01. Frontal theta/beta ratio change score was unrelated to all study measures.

Change in State Anxiety and Frontal EEG From Baseline to Social Stress Manipulation

As a manipulation check, we examined changes in children's state anxiety and frontal theta/beta

Table 1
Descriptive Statistics and Correlations for Main Study Measures

	2	3	4	5	*M* (*SD*)	Range	Skew	Kurtosis
1. Temperamental shyness (parent-report)	.08	.03	.14	−.11	11.60 (4.15)	5 to 22	0.34	−0.59
2. Frontal EEG theta/beta ratio change	—	−.02	−.01	.01	−1.44 (3.33)	−10.76 to 9.06	−0.18	1.21
3. State social anxiety (child-report)		—	.18*	.16*	5.18 (2.99)	0 to 10	0.33	−0.89
4. Trait social anxiety (child-report)			—	.37*	7.49 (3.17)	0 to 14	−0.27	−0.30
5. Trait generalized anxiety (child-report)				—	6.93 (3.62)	0 to 16	0.21	−0.43

Note. EEG = electroencephalography; M = mean; SD = standard deviation.
*$p < .05$.

ratio from baseline to speech anticipation. First, there was a significant increase in state anxiety from baseline, $M = 1.65$, $SE = .25$, to the speech anticipation period, $M = 5.19$, $SE = .24$, $t(150) = -11.05$, $p < .001$ (Figure 1A), suggesting the task was indeed psychologically stressful. Second, there was a significant decrease in frontal theta/beta ratio from baseline, $M = 11.60$, $SE = .40$, to the speech anticipation period, $M = 10.15$, $SE = .37$, $t(150) = 4.33$, $p < .001$ (Figure 1B), suggesting an increase in neurocognitive control.

In order to better understand whether the change in theta/beta ratio was driven by changes in beta and/or theta activity, we further examined changes in each frequency band separately for baseline to the speech anticipation period. These findings revealed there was a significant increase in frontal beta power from baseline, $M = 0.29$, $SE = .01$, to the speech anticipation period, $M = 0.34$, $SE = .02$, $t(150) = -3.23$, $p = .001$, but no changes in frontal theta power from baseline to the speech anticipation period, $t(150) = -0.69$, $p = .493$.

Interaction of Temperamental Shyness and Frontal EEG Theta/Beta Ratio Change

State Social Anxiety

The full model including all predictors and covariates was significant in predicting children's subjective nervousness during speech anticipation, $F(6, 145) = 2.94$, $p = .010$, $R^2 = .14$. As presented in Table 2, results revealed a significant interaction between temperamental shyness and theta/beta ratio change predicting child's state social anxiety, $\beta = -.05$, $p = .018$. As illustrated in Figure 2, simple slope analyses revealed that temperamental shyness was positively related to state social anxiety in children with large decreases in theta/beta ratio, $\beta = .25$, $p = .009$, but unrelated when children had mean levels of theta/beta ratio change, $\beta = .08$, $p = .191$, or increases in theta/beta ratio, $\beta = -.09$, $p = .264$.

Trait Social Anxiety Symptoms

The full model including all predictors and covariates was significant in predicting children's

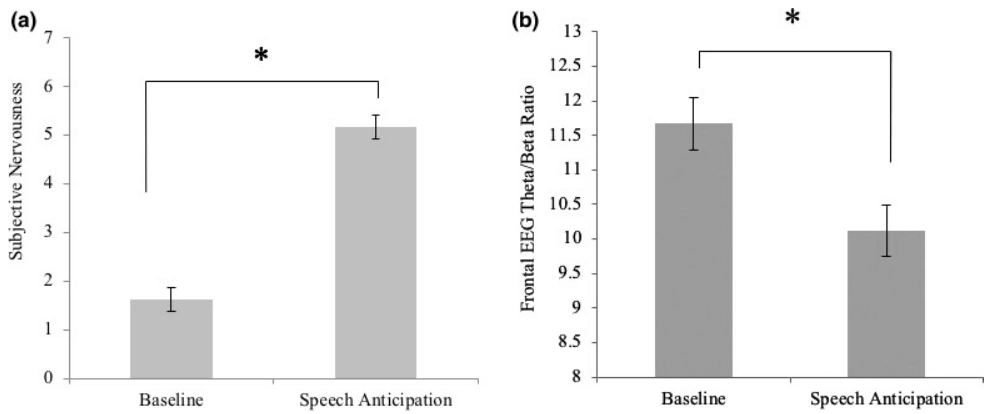

Figure 1. Baseline to speech anticipation changes in (A) children's state nervousness and (B) frontal electroencephalogram (EEG) theta/-beta ratio. Error bars reflect standard errors of the mean. Asterisks denote significant changes.

Table 2
Summary of regression models for temperamental shyness and frontal EEG theta/beta ratio change predicting (A) state social anxiety, and (B) trait social anxiety

	(A) State social anxiety					(B) Trait social anxiety				
Predictors	β	*SE*	*p*-value	R^2	ΔR^2	β	*SE*	*p*-value	R^2	ΔR^2
Step 1				.005	.005				.037	.037
Temperamental shyness	.026	.059	.660			.107	.062	.087		
EEG TBR change	−.023	.081	.776			−.017	.083	.841		
Step 2				.062	.057**				.127	.090**
Temperamental shyness	−.011	.761	.854			.049	.062	.424		
EEG TBR change	.464	.229	.043			.732	.219	.001		
Shyness × EEG TBR change	−.044	.019	.024			−.067	.018	< .001		
Step 3				.144	.083**				.189	.063*
Temperamental shyness	−.016	.058	.788			.052	.061	.394		
EEG TBR change	.453	.224	.044			.693	.220	.002		
Shyness × EEG TBR change	−.045	.019	.018			−.065	.018	< .001		
Sex	.100	.478	.835			−1.255	.493	.011		
Familial income	−.461	.165	.005			.005	.172	.976		
Child age	−.517	.548	.346			−.697	.569	.220		

EEG = electroencephalography; SE = standard error; TBR = theta/beta ratio.
$^*p < .05$. $^{**}p \leq .01$.

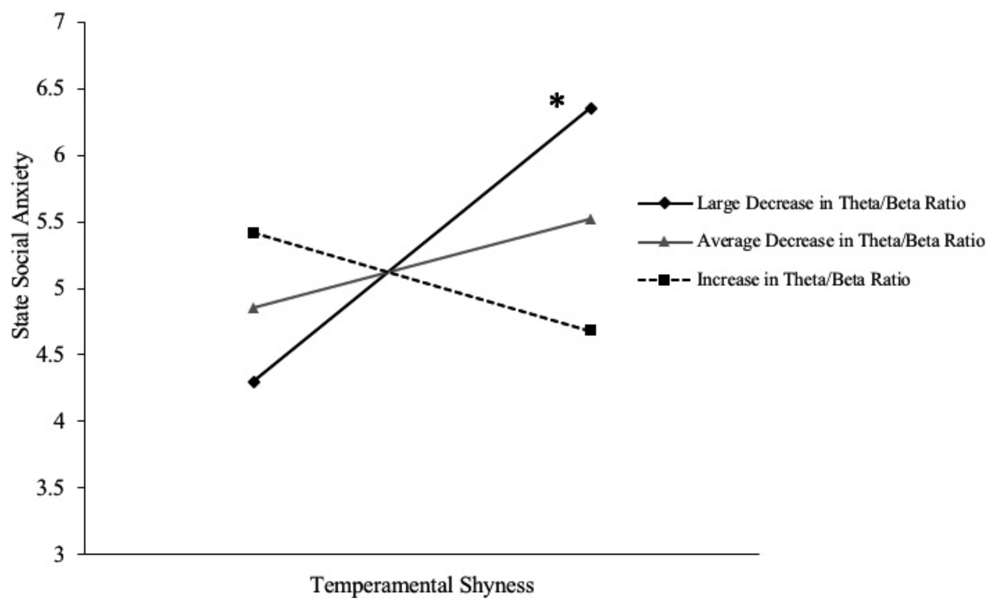

Figure 2. Moderating influence of children's frontal electroencephalogram (EEG) theta/beta ratio change from baseline to speech anticipation on the relation between temperamental shyness and state social anxiety. Lines plotted for an increase (+1 SD), average decrease (mean), and large decrease (-1 SD) in EEG theta/beta ratio. Asterisk denotes a significant slope.

symptoms of trait social anxiety, $F(6, 145) = 4.34$, $p < .001$, $R^2 = .19$. As presented in Table 2, results revealed a significant interaction between temperamental shyness and theta/beta ratio change predicting social anxiety symptoms, β = −.07, $p < .001$. As illustrated in Figure 3, simple slope analyses revealed that temperamental shyness was positively related to trait social anxiety symptoms in children with large decreases in theta/beta ratio, β = .40, $p = .002$, but unrelated when children had mean levels of theta/beta ratio change, β = .16, $p = .106$, or increases in theta/beta ratio, β = −.01, $p = .474$.

Supplementary analyses using baseline and speech anticipation theta/beta ratio scores

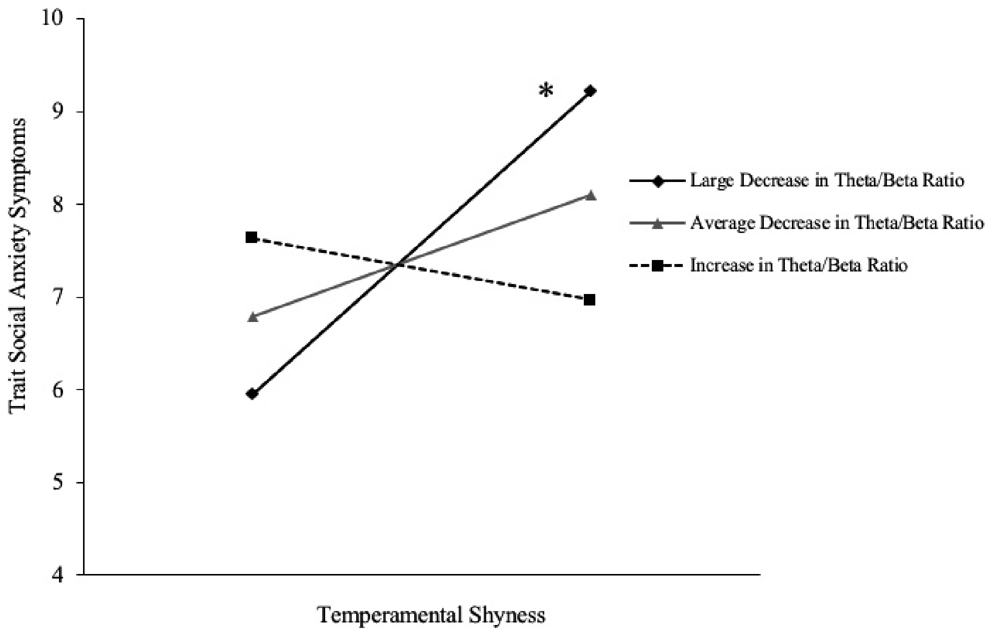

Figure 3. Moderating influence of children's frontal electroencephalogram (EEG) theta/beta ratio change from baseline to speech anticipation on the relation between temperamental shyness and trait social anxiety. Lines plotted for an increase (+1 SD), average decrease (mean), and large decrease (-1 SD) in EEG theta/beta ratio. Asterisk denotes a significant slope.

separately as moderators (as opposed to a change score) can be found in Tables S2 and S3.

Specificity Analysis

Generalized Anxiety Symptoms

The full model including all predictors and covariates was not significant in predicting children's symptoms of trait generalized anxiety, $F(6, 145) = 0.63$, $p = .710$. $R^2 = .03$. There was no significant interaction between temperamental shyness and theta/beta ratio change predicting generalized anxiety symptoms, suggesting specificity to social anxiety. See Table S1 for the full model.

Discussion

We examined how children's frontal EEG theta/beta ratio—an index of neurocognitive control—changed from baseline to a social stressor, and how individual differences in this change moderated the relation between temperamental shyness and risk of social anxiety. We found that children's frontal theta/beta ratio significantly decreased from baseline to the social stress induction and that individual differences in the magnitude of this theta/beta ratio change moderated the relation between temperamental shyness and social anxiety, but not generalized anxiety. Specifically, temperamental shyness was only related to higher levels of state and trait social anxiety among children who exhibited large decreases in frontal theta/beta ratio from baseline to the social stressor.

Frontal theta/beta ratio is thought to reflect the efforts of top-down control processes in cortical networks over bottom-up reactive processes in subcortical networks (Angelidis et al., 2016, 2018; Putman et al., 2010, 2014; Schutter & Van Honk, 2005). Our findings that children's frontal theta/beta ratio significantly decreased from baseline to the social stress induction may reflect greater cognitive control and mental effort required during the social stressor. Follow-up analyses revealed that this change in theta/beta ratio was driven by increases in beta ratio from baseline to the social stressor providing support that it may reflect greater cognitive control (Ray & Cole, 1985). This is in line with previous research examining the correlation between baseline frontal theta/beta ratio and behavioral and psychological indices of cognitive control (Angelidis et al., 2016; Cuevas et al., 2020; Perone et al., 2018; Putman et al., 2010, 2014). Likewise, it is also in line with a study among adults that reported task-related changes in frontal theta/beta ratio during an attentional task relative to a mind wandering task (van Son et al., 2019), providing support for theta/beta ratio as an index of neurocognitive control.

We further found that individual differences in the magnitude of this neurocognitive control moderated the relation between temperamental shyness and social anxiety risk at both the state- and trait-level. Temperamental shyness was only related to higher levels of social anxiety for children who showed relatively high levels of neurocognitive control in response to the social stressor. These findings can be interpreted in the context of the risk potentiation model of control which posits that cognitive control may serve as a risk factor for maladaptive socioemotional outcomes among children with reactive temperaments such as shyness (Buzzell et al., 2018; Henderson & Wilson, 2017; Henderson et al., 2015). Similar to a previous study examining temperamental shyness and neurocognitive control in middle childhood (Henderson, 2010), we did not find that temperamental shyness was directly related to levels of neurocognitive control. This provides support for the relative independence of reactive and controlled processes for children in our study.

The risk potentiation model of control suggests that reactive and controlled processes reinforce one another and thus higher levels of cognitive control among temperamentally shy children serves to potentiate risk for maladaptive cognitions related to fear and threat perception in social situations (Derryberry & Rothbart, 1997; Henderson & Wilson, 2017; Henderson et al., 2015). For example, enhanced cognitive control for shy children may result in excessive processing of threat-related social cues in their environment. These cognitions related to social fear may also result in rigid, overcontrolled social behaviors, and limit the child's flexibility for engaging with his/her social environment, possibly resulting in less positive social experiences. Over time, these social experiences may serve to reinforce children's perceptions and expectancies of social threat, which is a maintaining factor in social anxiety (van Niekerk et al., 2017). This may set the stage for higher levels of social anxiety for children while anticipating future social situations.

Our findings are also consistent with previous studies that have examined components of cognitive control as moderators of the relation between temperamental shyness and social behavior (e.g., Brooker et al., 2016; Hassan et al., 2020; Sette et al., 2018; Thorell et al., 2004; White, McDermott, et al., 2011). An extension of our study relative to previous studies is that we specifically examined neurocognitive control during a task designed to induce social-evaluative threat, which may mirror typical social stressors faced by shy children in middle childhood, such as anticipating social exposure and evaluation by peers. Although previous studies have indexed facets of cognitive control using laboratory tasks, these have indexed cognitive control in nonaffective conditions, using paradigms such as the Flanker Task and Go/NoGo Tasks (e.g., Henderson, 2010; Thorell et al., 2004; White, McDermott, et al., 2011; White, Royston, et al., 2011). We speculate that since we assessed neurocognitive control in a socially salient context, this may be one reason that our results were specific to *social* anxiety, and not generalized anxiety. Overall, our findings provide support that social anxiety may manifest for some children due to a competition between bottom-up reactive systems (i.e., temperamental shyness) and top-down regulatory attentional systems (i.e., neurocognitive control) particularly during social stressors.

The findings from this study have theoretical and practical implications. Identifying the neurocognitive processes that moderate the relation between shyness and anxiety may help to predict which shy children are at risk for anxiety problems. Future work should examine specific cognitive processes (e.g., threat perception, social self-efficacy) underlying the enhanced neurocognitive control among at-risk shy children reported in our study. Given that heightened neurocognitive control during social threat induction increases the risk for social anxiety among temperamentally shy children, altering the processes thought to underlie this change, such as social threat perception, may help to promote positive social adjustment among these children. For example, previous research has illustrated that frontal theta/beta ratio is amenable to change following biofeedback intervention (Janssen et al., 2017; Prinsloo, Rauch, Karpul, & Derman, 2013), and likewise cognitive behavioral therapy for social anxiety is related to a reduction in hypersensitivity to social threat (Asbrand et al., 2019; Klumpp, Fitzgerald, & Phan, 2013; Miskovic et al., 2011). Future work should examine if experimental interventions aimed at decreasing excessive neurocognitive control during socially threatening situations for shy children translates to lower levels of social anxiety.

The findings of our study should be interpreted with the following considerations in mind. First, this study was cross-sectional and thus lacks a definitive temporal sequence. That being said, our decision of the tested predictor, moderator, and dependent measures was based on theory. That is, temperament is typically conceptualized as an early precursor to prospective anxiety, and cognitive control is typically conceptualized as a moderator on the temperament-anxiety relation (e.g., Brooker et al., 2016; Henderson, 2010; Lahat, Walker, et al., 2014; Lamm et al., 2014; White, McDermott, et al., 2011), and so we likewise treated theta/beta ratio as a moderator on the shyness-anxiety relation. However, we acknowledge that given the cross-sectional nature of our study, we cannot infer the developmental timetable of the processes tested in this study nor causal relations. It will be important to investigate the brain-behavior relations reported here within a longitudinal framework in the future to better understand the directionality of the findings.

It should be also noted that although we interpret the baseline-to-task decrease in theta/beta ratio as indicative of greater neurocognitive control during the social stressor based on previous work finding relations between theta/beta ratio and cognitive control (Angelidis et al., 2016, 2018; Putman et al., 2014; van Son et al., 2019), we did not directly examine additional measures of attentional control outside patterns of EEG power. Relatedly, no previous work has examined changes in theta/beta ratio from baseline to a social stressor, and thus it is also possible that the change in theta/beta ratio reflects a stress response or change in affect. This may be similar to a previous study in typically developing children that found an increase in right frontal alpha power among shy children while they were anticipating a speech task, which is thought to reflect increases in negative affect and a withdrawal motivation (Schmidt et al., 1999).

Furthermore, our sample was fairly homogenous in terms of ethnicity, socioeconomic status, and age, which may limit generalizability to more diverse samples. Specifically, it will be important for future work to examine the relations reported here across different developmental stages, given changes in the development of cognitive control and social anxiety, as well as changes in the dominant frequencies across development (Gasser, Verleger, Bacher, & Sroka, 1988). As well, our EEG recording was approximately 2 min across conditions, which is a relatively short recording period. Relatedly, although our inclusion of children with 20 segments of clean EEG data may be considered somewhat low, we performed post hoc analyses that included only children with the recommended minimum of 40 segments of clean EEG data (Mocks & Gasser, 1984), and the significance and interpretation of our results remained unchanged. Finally, there remains debate regarding whether EEG can be used to measure subcortical processes, and we cannot be certain where exactly the electrical activity is originating from in the brain (Pizzagalli, 2007).

Conclusion

It is important to consider individual differences in children's temperament when examining the role of neurocognitive control on risk for anxiety. Temperamentally shy children who also have high levels of neurocognitive control appear to be at greater risk for social anxiety, possibly due to their tendency to overregulate during social encounters. Future work should continue to examine factors that serve as risk and resilience factors on the relationship between temperament and anxiety across development.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Table S1. Summary of Regression Model for Temperamental Shyness and Frontal EEG Theta/Beta Ratio Change Predicting Trait Generalized Anxiety

Table S2. Summary of Regression Models for Temperamental Shyness and Baseline Frontal EEG Theta/Beta Ratio Predicting (A) State Social Anxiety, and (B) Trait Social Anxiety

Table S3. Summary of Regression Models for Temperamental Shyness and Frontal EEG Theta/Beta During Speech Anticipation Predicting (A) State Social Anxiety, and (B) Trait Social Anxiety