LONGITUDINAL RELATIONS AMONG BEHAVIORAL INHIBITION, ERROR-RELATED NEGATIVITY, AND SEX IN PREDICTING SOCIAL ANXIETY AMONG CHIDLREN

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ABSTRACT

Because social anxiety is highly prevalent among children and adolescents, it is important to study early risk factors in infancy in order to better understand a developmental pathway to social anxiety. Behavioral inhibition (BI), a tendency to hesitate or avoid novelty and uncertainty, is a leading risk factor appearing in infancy. BI has been linked to social anxiety through heightened response monitoring for threat or error. This error monitoring can be operationalized by measuring error-related negativity (ERN). Additionally, as social anxiety does not appear equally in men and women, it is important to understand if there is an underlying sex difference in neural components like ERN, and how sex determines pathways of risk involving ERN, that accounts for the difference in prevalence rates. This study (112 children, 44.6% female, 85.7% White, 95.5% non-Hispanic) proposed that infant BI will predict social anxiety symptoms in early childhood, through larger concurrent ERN, and that sex will moderate this mediation, with the relation between ERN and social anxiety symptoms being stronger among female children. Results did not support either hypothesis, but did find that BI predicted later social anxiety symptoms. Non-significant findings are discussed in the context of developmental psychopathology theory of social anxiety.

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Longitudinal Relations among Behavioral Inhibition, Error-Related Negativity, and Sex in Predicting Social Anxiety among Children

Anxiety disorders can be debilitating to the people experiencing them, especially when they occur in childhood and adolescence. Among adolescents 13-18, an astounding 31.9% meet criteria for any anxiety disorder, and around 9% meet criteria for social anxiety disorder (Merikangas, et al., 2010). The core feature of social anxiety disorder is significant fear of negative evaluation in social situations, often resulting in avoidance or intense distress if unable to avoid (American Psychiatric Association, 2022). Social anxiety can be chronic, leading to difficulties throughout life (Schneier & Goldmark, 2015). As social anxiety disorder often first develops in adolescence, it is critical to recognize it early and provide the child treatment in order to prevent a lifelong struggle. One method for early detection of social anxiety is to study risk factors that appear in early childhood or even begin in infancy. If a developmental pathway for social anxiety is better understood, it could be possible to begin early prevention and treatment and reduce the risk of the child developing anxiety.

Behavioral Inhibition as a Risk Factor for Social Anxiety

Behavioral inhibition (BI) is the tendency to hesitate or avoid new situations and people (Kagan et al., 1984). Children express signs of BI during infancy. When coming in contact with a new person or situation, an infant with BI would be likely to stop their current activity, freeze up, go to a familiar and comforting person, or all together avoid the stimulus. Often, children with BI are thought of as shy or quiet. BI was initially characterized as an extreme end of a shyness spectrum, with an uninhibited, or extremely social and unrestrained child falling at the other end of the spectrum- but BI should be thought of as a distinct temperament separate from shyness (Kagan et al., 1989). BI is also moderately stable across childhood, as infants who express wariness in new situations are likely to continue to do so when they are four and seven years old; and can extend into adulthood (Fox et al., 2005; Fox et. al 2001). BI has been found to be strongly correlated with social anxiety, suggesting that children's wariness of new situations or people can develop into clinical levels of social avoidance, which demonstrates its utility as a risk factor (Biederman et al., 2001). Clauss and Blackford (2012) conducted a review and found support that BI predicts social anxiety, finding that more than 40% of children with high BI will be later diagnosed with social anxiety. Although early BI is one of the most prominent risk factors for social anxiety, there is a large portion of variance unaccounted for (Biederman et al, 1993; Fox & Pine, 2012). Kagan and colleagues (1987) first proposed that parts of the brain associated with novelty or threat detection could be the mechanism linking BI to anxiety. It is possible that BI predicts development in other systems, such as ones related to threat detection, which then more proximally predict social anxiety. Thus, this connection needs to be investigated more to find if such mechanisms can link BI to future social anxiety.

Error-Related Negativity as a Mechanism of Anxiety Risk

One possible mechanism linking BI and social anxiety is a heightened awareness of or response monitoring for threat. Because behaviorally inhibited children are more hesitant and wary of new situations, they may react to novelty by being on constant high alert for any new situations they might encounter. Indeed, Fox and colleagues (2020) found that children high in BI are more likely to be on high alert for new or threatening situations. This heightened alert further extends to a heightened physiological response to novel stimuli, including faces and sounds (Fox et al, 2021; Reeb-Sutherland et al., 2015). This constant state of arousal could be one factor linking BI and social anxiety.

A more specific mode of this heightened physiological response towards novel or threatening stimuli involves a heightened attention towards mistakes, called error monitoring. Error monitoring can be measured as a neural response to incorrect answers during tasks, measured by electroencephalography (EEG) recordings (Meyer et al., 2015; Weinberg at al., 2010). This neural response is known as error-related negativity, or ERN. ERN is a large negative voltage peak that occurs when an individual makes an incorrect response on a task, typically peaking 0-100ms after the response (Brooker & Buss, 2014; Meyer, 2017). Error monitoring happens unconsciously, and a more pronounced (more negative) ERN can suggest an over-concern for negative evaluations (Brooker & Buss, 2014). Because ERN occurs unconsciously and is measured neurologically, it does not rely on self-report, which can minimize reporting bias when assessing social anxiety in children.

The Detection and Dual Control (DDC) framework theorizes how such salience detection directly links infant temperament to social anxiety development (Fox et al., 2023). The framework suggests that children with BI are more biased towards error monitoring, a type of salience detection, than non-BI children, which then leads to anxiety symptoms. A hypervigilance towards error detection can result in more avoidance or freezing during such novel or threatening situations (Fox et. al, 2021). The self-reinforcing behavior of avoidance or freezing when facing a threatening situation can strengthen a child's error monitoring over time, and thus lead to the development of social anxiety.

ERN has been suggested to be a biomarker of anxiety disorders, and its presence can uniquely classify a child with anxiety symptoms from a child with depressive symptoms (Bress et al., 2013). Meyer and colleagues (2012) additionally found support that ERN can be a biomarker for anxiety, as the two were correlated, and this correlation strengthened with age among 8–13-year-olds. In order to examine if ERN can serve as a predictor of anxiety, rather than just a concurrent biomarker, Meyer and colleagues (2015) further studied ERN longitudinally, finding that more extreme ERN measured at age 6 predicted anxiety symptoms 3 years later. Additionally, ERN was found to predict generalized anxiety symptoms, a disorder that commonly co-occurs with social anxiety, 1.5 years later among female adolescents, further supporting the use of measuring ERN as a concurrent and predictive risk factor for anxiety across various stages of childhood (Meyer et al., 2018).

It is important to note that while BI and ERN can both be thought of as heightened awareness for novelty or threat, they are distinct processes associated with different areas of the brain that develop at different points in time. BI has been connected to activity in the amygdala, the area of the brain associated with fear (Fox et al., 2023). Thus, when children are behaviorally inhibited, they are responding to novel stimuli with enhanced fear (Fox et al., 2005). ERN, on the other hand, has been linked to the anterior cingulate cortex (ACC), an area of the brain associated with threat, pain, and punishment (Meyer et al., 2022). This suggests that when children have heightened ERN, they are reacting to the threat or potential punishment that accompanies an error, in order to learn or modify their future behavior (Meyer et al., 2022). The ACC develops and matures later than other areas of the brain, including the amygdala, which may explain why measures of ERN in children are smaller than measures of ERN in adults, as it is still developing across childhood (Davies et al., 2004).

While BI and ERN have been separately supported as predictors for later social anxiety (Clauss & Blackford, 2012; Meyer et al., 2015), less research has focused on models involving both predictors, which could determine whether ERN accounts for the missing variance in longitudinally BI predicting social anxiety. One theory from Meyer (2017) states that as children get older, their fears switch from the external, like phobias or separation anxieties, to more internal fears, such as behavioral or performative fears, like making a mistake; this switch is linked to an increase in ERN during this time. The age that this switch occurs- which Meyer estimates around age 6 to 9- may be an important time to examine ERN as a predictor of social anxiety. Because an age for this change is not confirmed, research is needed to investigate the relations among BI, ERN and social anxiety across childhood and adolescence. Buzzell and colleagues (2017) found that the relation between infant BI and anxiety at age 12 was mediated by adolescent ERN. This however, is one of the only studies investigating this mediation, and does not explore the lower bounds of age per Meyer's theory to see if this relation appears in younger childhood.

Thus, there is burgeoning, but limited, evidence to suggest that a longitudinal pathway exists among BI, ERN, and social anxiety; continued investigation is needed. The existing research tends to focus on older children, as there is no such study that measures anxiety and ERN in younger children. More work is needed to fully understand the extent of this pathway and whether this relation is evident earlier in childhood.

Potential Sex Differences in Anxiety Risk Pathways

Social anxiety disorder does not impact male and female individuals equally. Social anxiety is typically more prevalent among women than among men, with adult women having a 50- 120% greater chance of being diagnosed compared to adult men; this difference is even more profound among adolescents (American Psychiatric Association, 2022; Schneier & Goldmark, 2015). There have been recent efforts to investigate if sex assigned at birth (hereafter referred to as sex) relates to neural processes that account for the difference in prevalence rates. Of note, until recently, prior research has often used sex and gender terms interchangeably (and the terms used in the original studies are used when subsequently reviewing the literature), but for this study, only sex will be used. Moser and colleagues (2016) found a difference in the relation between ERN and anxiety among adults, in that women, but not men, with higher rates of anxiety also had more negative ERN. Meyer and colleagues (2018) found that adolescent girls with larger ERN magnitude were more likely to be diagnosed with generalized anxiety disorder, compared to girls with smaller ERN magnitude. The results from these studies suggest that this relation between ERN and anxiety is not the same in men and women. There is a lack of research on this sex difference in younger populations, and it would be beneficial to test if a difference in ERN magnitude, or a difference in the relation from ERN to social anxiety, extends to children.

Research Aims and Hypotheses

Despite their inclusion in theories on social anxiety development, and support for each separately as a predictor, previous literature has not included BI, ERN, and sex together as predictors for later social anxiety. Additionally, little research in this area includes early childhood populations when measuring ERN and anxiety symptoms. This gap in research has led to the following research questions.

1) Is there is a longitudinal pathway from BI to ERN and social anxiety, such that higher BI predicts more negative ERN, which then relates to concurrent social anxiety symptoms?
2) As evidence for a relation between ERN and anxiety is stronger for women, does sex moderate this relation in younger children?

From these research questions I therefore hypothesized that BI will predict social anxiety symptoms through ERN, such that that high BI in infancy will predict more negative ERN in early childhood, which will then relate to increased social anxiety symptoms in early school-age. I further hypothesized that sex will moderate this mediation, with the relation between ERN and social anxiety symptoms being stronger among female children than among male children. See Figure 1 for a model of the proposed moderated mediation.

Methods

Participants

Two hundred thirty participants were included in the initial data set, as part of an ongoing longitudinal study consisting of seven phases defined by age. Participants were initially recruited from the community at local farmers' markets, Women Infant and Children (WIC) events, local birth announcements, and flyers at doctors' offices and daycares. This study utilized data from laboratory visits when children were 1 years old (*M*= 14.14 months *SD*= 1.28), 2 years old (*M*= 26.65 months *SD*= 1.77), and 5-6 years old (*M*= 65.17 months, *SD*= 4.15).

Twenty-four participants were excluded for having siblings in the data set (there were 22 sibling dyads and 1 triad). Siblings were evaluated on who had more complete data, who had completed the EEG task, who had a higher anxiety score, if any sibling was female, or if there were no differences, which sibling was recruited first, in order to determine which sibling to retain. Ten participants were excluded for missing all of the primary variables, 2 were excluded for autism spectrum disorder diagnoses, 1 was excluded for potential opioid exposure at birth, and 1 was excluded for being especially fatigued during study visits, leaving 192 participants remaining. Data was then evaluated for missingness. Because there was a high number of participants missing data for primary variables (68.7% of data was missing for ERN and 47.2 % of data was missing for social anxiety), only participants with at least 1 data point during the age 5 visit were kept, resulting in 112 participants in the final sample.

Mothers reported their own age at the birth of their child participating in the study (*M*= 30.38 years, *SD*= 5.15). Mothers self-reported various demographics for themselves and their children at their first visit. Children in the sample are 44.6% female, 85.7% White, and 95.5% non-Hispanic. Mothers in the sample are 93.8% White and 99.2% non-Hispanic. Additionally, mothers reported annual household income and education level at each study visit. Reported income was averaged across study visits, and mother's highest reported degree earned was used to represent socio-economic status. There was a wide range of reported average incomes, from below \$15,000 to above \$100,000, with a mean average income of \$51,000-\$60,000. There was also a wide range of maternal maximum education level, from completing 9th grade to earning a doctorate degree, with a median education level of earning a college degree.

Procedure

Tasks completed for this study are part of a larger longitudinal study with additional tasks. Only applicable tasks are included in this procedure. Mother-infant pairs came in person to the laboratory for each visit. At the beginning of every visit, a trained graduate student received consent from mothers, and although there was no formal document to sign, assent from children starting at the age 5-6 visit. Enrollment was ongoing, with dyads able to start during any of the first four phases of the larger study.

At the first and second lab visit when children were 1 and 2 years old, dyads completed a battery of five episodes for an observational measure of behavioral inhibition (Fox et al., 2001). In episode one, the child is given several toys to play with for 5 minutes of free play; in episode two a stranger enters the room and is silent for 1 minute; in episode three the stranger invites the child to play with a toy dump truck for 2 minutes; in episode four, the stranger invites the child to play with a remote-controlled robot for 2 minutes; and in episode five, the stranger invites the child to crawl inside a tunnel for 1 minute. The child's mother was in the room during the entire battery but was asked to remain neutral and not direct the child's behavior. At the end of the visit, mothers were compensated $40 (age 1) or $50 (age 2), and children received a small toy.

During the age 5-6 lab visit, children completed an EEG, administered by trained graduate students. Children were fitted with a 32-channel Hydrocel Geodesic Sensor net (Electrical Geodesics, Inc.). Impedances were reduced to 50Ω before data acquisition. Data were referenced to the Cz electrode during recording. Children first completed a 6-minute baseline measure (alternating between "eyes open" and "eyes closed" 1-minute segments), followed by a modified flanker task (Brooker & Buss, 2014) presented on a computer screen. For the flanker task, children were instructed that five fish would appear on the computer screen and that they should "feed" the target middle fish by pressing the right button on a keypad if the fish is facing right, and the left button on the keypad if the fish is facing left. Children were told to feed the fish as fast as possible; the time pressure creates a greater chance of errors, which are required to score ERN. After each trial, a picture of a smiling or frowning woman appeared to denote a correct or incorrect response, respectively. Children began with 16 practice trials while an experimenter was in the room to ensure they understood the directions. The experimenter then left the room, and the child completed 2 blocks of 64 trials. Trials were distributed across "congruent" and "incongruent" flankers, where flanking fish either faced the same or opposite direction as the middle fish, respectively. Before each trial, a fixation cross appears for 400ms, followed by the fish appearing on screen for 1000ms. During the practice trials, the target fish appear for 1700ms. The participant responds, and after a 1000ms delay, a happy or sad face appears for 1500ms to denote a correct or incorrect response, respectively. There is another 1000ms delay before the next trial begins. See Figure 2 for an outline of the task. If a child grew tired of the task, they were allowed to stop with no penalty.

Also during age 5-6 visits, parents completed a measure of their child's anxiety symptoms using the social anxiety subscale of the Preschool Anxiety Scale (Spence et al., 2001). After data collection, mothers were compensated $50 and children were given a small toy prize.

Measures

Sex Assigned at Birth

Child's sex was recorded from birth announcements, or from mother's report when they first scheduled their laboratory visits.

Behavioral Inhibition

A composite BI score was determined through coding four episodes of the observational task for a variety of behaviors, listed below (Fox et al., 2001). Coders used INTERACT (Mangold, 2022) to score episodes on a frame-by-frame basis for the presence of various behaviors. Behaviors were coded for the following parameters: latency of first instances of behaviors (in seconds), count (number of distinct times that behavior was present), and duration (across all instances, total number of seconds behavior was present). These subcomponents were subjected to principal component analysis to identify a group of behaviors that loaded together to explain variance. Sixteen behaviors across the stranger, robot, and tunnel episodes were used to create the final composite score (during stranger- latency to approach stranger, latency to touching stranger the first time, duration of being within arm's length of stranger while playing, duration of being within arm's length of mother when not playing, count of non-distressed vocalizations, duration of freezing, duration of vigilant stare; during robot- latency to approach robot, latency to touching robot for the first time, duration of being within arm's length to stranger while playing, duration of being within arm's length of mother when not playing, duration of freezing, duration of vigilant stare, touching robot duration; during tunnel- duration of being within arm's length of mother when not playing, duration of freezing). Interrater reliability was high across all behaviors, with all ICCs above .90. Number of vocalizations, duration of time playing in proximity of stranger, and duration of time touching robot were all reverse scored so that higher scores aligned with other behaviors to indicate higher inhibition.

After behaviors were reversed and standardized, behaviors were averaged to create final composite of behavioral inhibition. For dyads that completed the battery at both age 1 and age 2 visits, composite scores will be averaged across the two visits for a final score.

Error-Related Negativity

Offline, all EEG data was processed and scored using EEGLAB (Delorme & Makeig, 2004) and the ERPLab plugin (Lopez-Calderon & Luck, 2014) for MATLAB software (The MathWorks Inc., 2022). To determine ERN, based on contemporary research methodology (Buzzell et al., 2017; Fillippi et al., 2020; Meyer et al., 2021), EEG data was bandpass filtered between 0.10 and 30 Hz, and artifacts such as eyeblinks and eye movements were removed using Independent Components Analysis., with an average of 2 components removed. Data were manually inspected for any channels with flat lines or with excessive noise, which were interpolated. Data were re-referenced to the average of all electrodes. Data were then segmented from 200ms prior to participant response to 1000ms after the response, and baseline corrected using a window of -200 to 0ms before the response. Trials were further rejected for the following- voltages exceeded ±200 V within a trial, a voltage difference of 150 μV within a trial, and a voltage step of more than 75 μV between data points in a trial. Any participant without the minimum trials needed for accurate scoring of ERN (6 correct trials, 6 incorrect trials; Pontifex et al., 2010), were considered to be missing. In line with Isbell and Grammer's (2022) finding that using a time window mean amplitude produces higher quality data in children than using peak amplitude, for incorrect and correct trials, ERN and correct-response negativity (CRN) respectively, were calculated as the average of the mean amplitude from 0-100ms after the response on Fz and FCz channels. The final variable is the difference between ERN and CRN values.

Prior research has found ERN derived from the flanker task to have moderate test-retest reliability (.63) across two years, and high convergent validity with a similar ERN task (go/no-go; .70) in children and adolescents (Meyer et al., 2013; Meyer et al., 2014).

Social Anxiety Symptoms

Social anxiety symptoms were from the social anxiety subscale of the Preschool Anxiety Scale (PAS, Spence et al., 2001). The PAS social anxiety subscale is a 6-item parent-report measure of social evaluative concerns. Items are scored on a 5-point Likert scale ranging from 0 (*not true at all*) to 4 (*very often true*). Scores range from 0 to 24 with higher scores indicative of greater social anxiety symptoms. Sample items include "worries he/she will do something to look stupid in front of other people", "is scared to ask an adult for help", and "is afraid of talking in front of the class". The PAS has been found to demonstrate high construct validity for measuring anxiety, as it significantly correlated to the CBCL Internalizing scale (.68), a well-known and reliable measure of broader internalizing problems in children (Spence et al., 2001). The PAS social anxiety subscale also significantly correlated with the CBCL Internalizing scale (.57; Spence et al., 2001). Internal consistency in the current study was found to be high (α = .85).

Results

Power and sample size considerations for moderated mediations are complex. Several approaches were taken to determine power. First, using G*Power (Faul et al., 2009), an a priori sample size calculation was conducted on the more complex of the two regression models involved in the mediation (regression predicting outcome of social anxiety). This model contained 4 predictors. Thus with 4 predictors, an alpha of .05, an estimated medium effect size, and desired power of .80, a sample size of 85 would be required to detect a significant coefficient above and beyond the other predictors in the model. Granted, the term of interest in an interaction term, and is more difficult to detect than other predictors, but the sample size of 112 is still well above the minimum required. Because the sample size is already known, a sensitivity analysis for the same regression model was also conducted in G*Power, which suggested that for a sample of 112 and an alpha of .05, a power of .80 would detect small effect sizes of .11 for any particular predictor above and beyond other predictors. Next, an a priori power analysis was conducted on the indirect effect. Using correlations from previous studies of BI, ERN, and social anxiety, a priori Monte Carlo power analysis (Schoemann et al., 2017) suggested that a sample size of 66 would give sufficient power. This does not include the moderation piece, so a larger sample would likely be needed to be moderately powered.

During pre-processing of ERN data, 4 participants were considered missing for having no recorded events, and 2 participants were considered missing for their recordings only containing noise. In line with Pontifex and colleagues' (2010) suggestion, 10 participants were counted as having missing values for ERN for not meeting the minimum number of 6 trials necessary for ERN calculation. Also of note, 2 participants were accidently recorded using a 64-channel net. Their data was analyzed separately with the same parameters as the 32-channel data, with necessary adjustments for number of electrodes or electrode placement (i.e. calculating average ERN on Fz and FCz used channels 4 and 6 with the 64-channel data instead of channels 17 and 28 used with the 32-channel data). These 2 participants had their ERN difference calculated but are not included in the ERN grand average waveform (see Figure 3).

Participants that were excluded from the final sample of 112 were compared to those that remained in the sample. Excluded participants had significantly lower maternal education level (M = 14.87, SD = 2.77) than participants that remained in the sample (M = 15.84, SD = 2.55), $t(185)$= 2.49, p = .007, Cohen's d = 2.64 95% CI [0.20, 1.76], but did not significantly differ on any other characteristic. Remaining missing values among the analytic sample of 112 were handled in primary models by using full information maximum likelihood (FIML) estimation.

Data were inspected for normality. Skewness and kurtosis for both dependent variables (ERN skew = 0.07, kurtosis = 1.18; social anxiety skew = 0.72, kurtosis = -0.16) did not demonstrate extreme deviations from normality (skew < 3 and kurtosis < 10 respectively), so no transformation was required. Descriptive statistics are reported in Table 1 for all variables. Correlations among demographics, ERN, and social anxiety symptoms, as well as independent sample t-tests for dichotomous variables or one-way ANOVAs among categorical variables with more than two levels, were evaluated to see if any demographics should be used as a covariate in the model. See Table 2 for bivariate correlations. None of the test variables significantly differed on any demographic, so no covariates were added to the model. Correlations between primary variables were assessed. BI did not significantly correlate to ERN (r =.058, p =.694). ERN did not significantly correlate with social anxiety (r =.096, p = .470). BI was marginally correlated to social anxiety (r = .203, p = .060).

Primary analyses of a moderated mediation were completed in Mplus (Muthén & Muthén, 1998-2017) with guidance from Hayes (2022) and Hayes and Preacher (2013). Path coefficients were tested, and symmetric confidence intervals are provided. Indirect effects were tested with a bootstrapping approach (10,000 bootstraps) to create confidence intervals.

Sex did not significantly moderate the relation between ERN and social anxiety, $b = 0.02$, S.E = 0.14, $t = 0.16$, $p = .872$, 95% CI [-0.25, 0.29]. This model produced a warning of a non-positive definite first-order derivative product matrix, but the model estimation terminated normally. The problematic parameter was the interaction term, and since the interaction was nonsignificant, it would be dropped in subsequent models anyway. Estimates of absolute and relative model fit ($\chi^2 = 32.78$, $p = .000$, RMSEA= .371, CFI= .00, TLI= -2.55) suggested poor model fit (Hu & Bentler, 1999).

Because sex did not moderate the relation between ERN and social anxiety, the interaction was removed, and a simple mediation model was assessed. ERN did not significantly mediate the relation between BI and social anxiety, ab = 0.01, *S.E* = 0.024, $t = 0.19$, $p = 0.852$, 95% CI [-0.21, 0.75]. BI, however, did marginally predict social anxiety above and beyond ERN, $c' = 1.94$, *S.E* = 0.10, $t = 1.91$, $p = .056$. Model fit was just identified, so estimates are not reported.

Post-hoc analyses assessed if sex, instead of moderating the *b* path, moderated the *a* path of the mediation model, between BI and ERN. Sex did not significantly moderate the relation between BI and ERN, $b = 0.06$, *S.E* = 0.12, $t = 0.49$, $p = .622$, 95% CI [-0.18, 0.30]. Estimates of absolute and relative model fit ($\chi^2 = 1.04$, p=.594, RMSEA= .00, CFI= 1.00, TLI= 1.00) suggested exact model fit (Hu & Bentler, 1999).

Discussion

This study aimed to address if there was a longitudinal pathway from BI to ERN and social anxiety, and if sex moderated this relation. I hypothesized that BI would predict social anxiety symptoms through ERN, such that that high BI in infancy would predict more negative ERN in early childhood, which would then predict increased social anxiety symptoms in early childhood. I also hypothesized that sex would moderate this mediation, with the relation between ERN and social anxiety symptoms being stronger among female children than among male children. Results did not provide support for either hypothesis. Post-hoc analyses were also tested to examine if sex moderated a different pathway in the mediation model; however this was also not supported by results.

Sex was not found to be a significant moderator in the model. This contrasts with adolescent and adult research showing that sex impacted the relation between ERN and anxiety (Meyer et al., 2018; Moser et al., 2016). It was unknown if similar results would be replicated with children, as this is understudied among this population. Previous work has found that social anxiety sex/gender differences are small among pre-school aged children, and larger sex/gender differences do not increase until age 12 (Schneier & Goldmark, 2015). Participants in this study were under age 12, so it is likely that sex/gender differences in social anxiety prevalence are not yet noticeable.

For this study I focused on sex assigned at birth. It is possible that gender, rather than sex, plays more of a role in the development of social anxiety. Social anxiety relates to social concerns about one's behavior. If there is a difference in the way boys and girls are socialized, such as emotion expression or how much focus is placed on evaluation from others, gender might serve as a better moderator in the model as compared to a biological focus like sex. It may be that girls are socialized to express their anxious feelings more often or are taught to be much more aware of any errors they make. Future research may want to explore differences in how sex versus gender impacts social anxiety development.

Social anxiety disorder typically first appears around age 13 (American Psychiatric Association, 2022). Although children may display symptoms associated with social anxiety at younger ages, 5 years old may be too early to display clinical levels of social concerns. This sample reported low levels of social anxiety symptoms, suggesting that they may not yet be experiencing significant social worries. Future studies may want to measure social anxiety symptoms and ERN at ages older than 5 to explore if the moderated mediation appears before age 12.

Results contradict previous studies that found the relation between infant BI and anxiety at age 12 was mediated by adolescent ERN (Buzzell et al., 2017)- however the children in this study were much younger when ERN and anxiety were measured, at age 5. It is possible that 5 years old is too young to demonstrate similar effects. Meyer (2017) theorized that children switch from external fears to internal fears between the ages of 6 and 9, and this change is also associated with an increase in ERN; this sample is potentially just shy of this change, and results may have been more in line with prior research if the children had been only one year older. Further, ERN develops throughout childhood, and graphs of the ERN grand average do not resemble that of adults until later into adolescence (Davies et al., 2004).

BI marginally correlated with social anxiety symptoms, and was a marginally significant predictor of social anxiety in the mediation model, once ERN was included. The relation between BI and social anxiety, while marginal, is in line with prior research that routinely establishes BI in infancy is one of the strongest predictors of later social anxiety (Biederman et al., 2001; Clauss and Blackford, 2012; Fox & Pine, 2012). Participants were not oversampled for social anxiety, resulting in low levels of reported social anxiety symptoms, with 13% of participants reporting zero social anxiety symptoms. This may account for the relatively weaker correlation in the present study compared to previous studies. The relation may be stronger in sample with a more equal spread of reported social anxiety symptoms. This study also used a community sample where anxiety levels tend to be lower than those seen in a clinical sample. A clinical sample may display a stronger relation between BI and social anxiety.

Although BI is moderately stable across childhood, it is possible that the length of time between when BI and both ERN and social anxiety were measured in this study impacted the strength of the model (Fox et al., 2005; Fox et. al 2001). This study measured BI at ages 1 and 2, and measured ERN and social anxiety at age 5. Given the fact that things measured temporally closer together tend to correlate more strongly, if I used a measure of BI closer to the other timepoint, such as age 3 or 4, BI may have been more strongly correlated to social anxiety, and the mediation may have found to be significant.

The moderated mediation model for this study was based on a larger theoretical model proposed by Fox and colleagues (2023). In the hypothesized expansion to the DDC framework, Fox posits that there are additional factors that affect the relation between BI and anxiety- such as parental characteristics, parenting and socialization, and cognitive control strategies- that were not included for this study. The tested model may have been too simplified without the other variables to produce any significant effects. Future studies may want to test the full DDC framework to explore if it accounts for the missing variance in predicting which inhibited children develop social anxiety.

Results may have been limited by the missingness of the ERN data. To account for the high rate of missingness, only participants that had data for either social anxiety or ERN were retained. Even after retaining participants that completed at least one of these age 5 visit data points, there were still only 63 participants with ERN data, leaving 44% of participants missing data. One explanation for this level of missingness relates to many of the age five visits occurring during the COVID-19 pandemic. It is possible that families were not comfortable or willing to physically come to the laboratory to complete an EEG that requires a researcher to come in close contact with the child. Many families chose to only complete online questionnaires during this phase of the study rather than coming into the laboratory for the full research battery. If ERN data collection occurred fully outside of the COVID-19 pandemic, it is possible that there would be fewer missing ERN values.

It is also possible that the parameters used in processing ERN data- such as the artifact detection windows, the 0-100ms time window used to determine ERN, and using mean amplitude to determine ERN- were too conservative and thus limited findings. While there are some explorations into determining the most effective parameters to use while processing child ERN data (Brooker et al., 2019; Isbell & Grammer 2022), there are no set parameters in the field. As a result, there is some variability across how researchers process their data. Specific parameters for this study were chosen based on the most common parameters found across the literature (i.e. Brooker et al., 2019; Buzzell et al., 2017; Fillippi et al., 2020; Isbell & Grammer 2022; Meyer et al., 2022). It is more difficult to attain sufficient data with children than with adults, as the data contain more noise and artifacts that needs to be removed, when compared to adult ERN data (Brooker et al., 2019). While this study used preset windows for artifact detection with some manual inspection and adjustments as needed, an alternative approach is to manually inspect and clean all trials individually (Brooker et al., 2019). This approach allows for adjustments made to the artifact detection and rejection process and may be more precise for processing; however it would have been incredibly time-consuming for the number of trials and participants in the data set, and it would have decreased standardization across participants. Another alternative processing approach is to collapse across all trials and visually inspect the average waveform to pick the time window for determining ERN amplitude (Brooker et al., 2019). This approach may allow for more precision selecting a time window that fits with the present data. However, the selected window may be different from the time window found most often in prior research (i.e. 0-100ms after a response; Brooker & Buss, 2014; Meyer, 2017), which would limit comparisons to other research studies. It may also lead to increased Type I error rate, if capitalizing on sample-specific patterns. One last alternative step for processing is to use peak-based amplitude rather than time window mean amplitude when determining ERN. Mean amplitude tends to be favored as the more effective approach among the two for producing higher-quality data, but it is possible that peak amplitude could have captured individual difference in the data set that mean amplitude did not (Brooker et al., 2019; Isbell & Grammer 2022).

Despite the lack of significant results and present limitations, this study is still beneficial to the literature on the relation between BI and social anxiety. It demonstrates the lower limits of when this relationship is evident in children. Because there are very few studies on this relation between BI, ERN, and social anxiety among children, future research may want to continue to explore this across childhood, especially before age 12. This may help us better understand how social anxiety develops among behaviorally inhibited children.

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Table 1
Descriptive Statistics for Study Variables

Measure	*n*	*Mean (SD)*	*Range*	*Skewness*	*Kurtosis*
ERN	63	-0.18 (3.99)	-10.62 – 12.44	0.07	1.18
BI	89	2.52 (0.55)	-1.31 – 1.21	0.42	-0.23
PAS Social Anxiety	108	6.24 (4.87)	0 – 20	0.72	-0.16
Income Average	110	5.53 (3.24)	0 – 10	-0.07	-1.29
Mom Education Max	112	15.85 (2.55)	9 – 21	-0.05	-0.27
Mom Age at Birth	112	30.38 (5.15)	17.27 – 43.91	-0.04	0.05
Child Age at 1-yr visit (months)	64	14.14 (1.28)	12.02 – 17.25	0.33	-0.83
Child Age at 2-yr visit (months)	84	26.65 (1.77)	24.18 – 32.62	1.19	1.37
Child Age at 5-6 yr visit (months)	73	65.17 (4.15)	58.68 – 75.37	0.32	-0.96

Note. ERN = error related negativity. BI = behavioral inhibition.

Table 2
Bivariate Correlations among Study Variables and Demographics

Measure	1	2	3	4	5	6	7	8	9
1. ERN	--								
2. PAS Social Anxiety	.10	--							
3. BI	.06	.20	--						
4. Income Average	.02	.06	-.04	--					
5. Mom Education Max	.16	.02	-.06	.62**	--				
6. Mom Age at Birth	.01	-.09	-.02	.61**	.49**	--			
7. Child Age at 1-yr visit	-.41*	.02	.14	.15	-0.01	.11	--		
8. Child Age at 2-yr visit	-.07	.07	.18	.01	-.10	.03	.55**	--	
9. Child Age at 5-6 yr visit	-.17	.21	.14	.01	0.03	-.18	.12	.23	--

Note. ERN = error related negativity. BI = behavioral inhibition.
**p* < .05, ***p* < .01.

Table 3

Regression Coefficients of Behavioral Inhibition, Error-Related Negativity, and Sex on Social Anxiety

	Estimate	*SE*	*t*	*p*	95% CI
Moderated Mediation analysis DV= Social Anxiety					
ERN	0.08	0.16	0.48	.633	[-0.23, 0.38]
BI	0.19	0.10	1.84	.066	[-0.01, 0.39]
Sex	-0.07	0.10	-0.72	.475	[-0.25, 0.12]
ERN x Sex	0.02	0.14	0.16	.872	[-0.25, 0.29]
Post Hoc Moderated Mediation on a path DV= Social Anxiety					
ERN	0.09	0.13	0.73	.468	[-0.16, 0.35]
BI	0.15	0.12	1.19	.235	[-0.10, 0.39]
Sex	-0.06	0.10	-0.67	.500	[-0.25, 0.12]
BI x Sex	0.06	0.12	0.49	.622	[-0.18, 0.30]
Mediation Model DV= Social Anxiety					
ERN on BI (*a*)	0.05	0.15	0.36	.723	[-0.26, 0.33]
Social Anxiety on ERN (*b*)	0.08	0.11	0.74	.458	[-0.14, 0.31]
Social Anxiety on BI (*c'*)	0.19	0.10	1.90	0.056	[-0.02, 0.38]
Indirect Effect (*ab*)	0.01	0.02	0.19	0.852	[-0.21, 0.75]

Note. ERN = error related negativity. BI = behavioral inhibition.

Figure 1
Proposed moderated mediation model

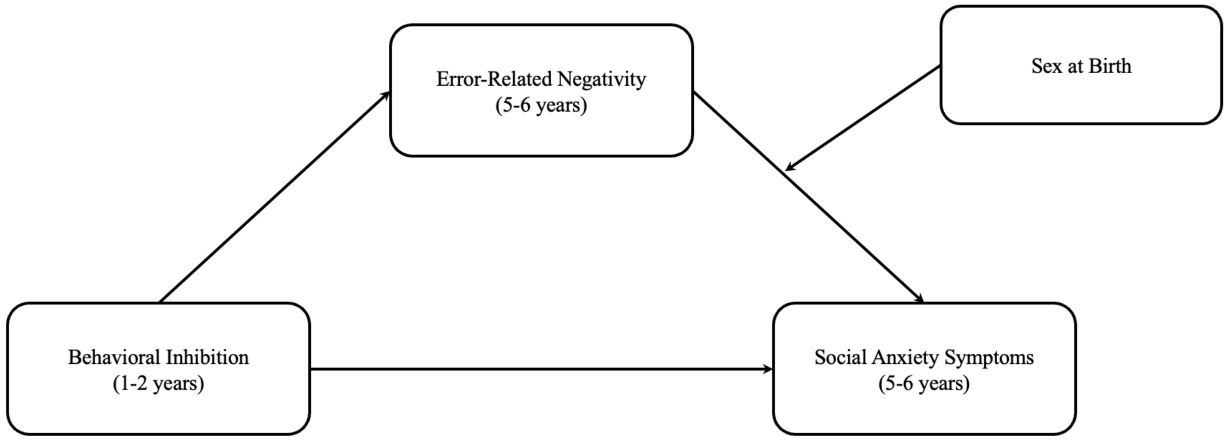
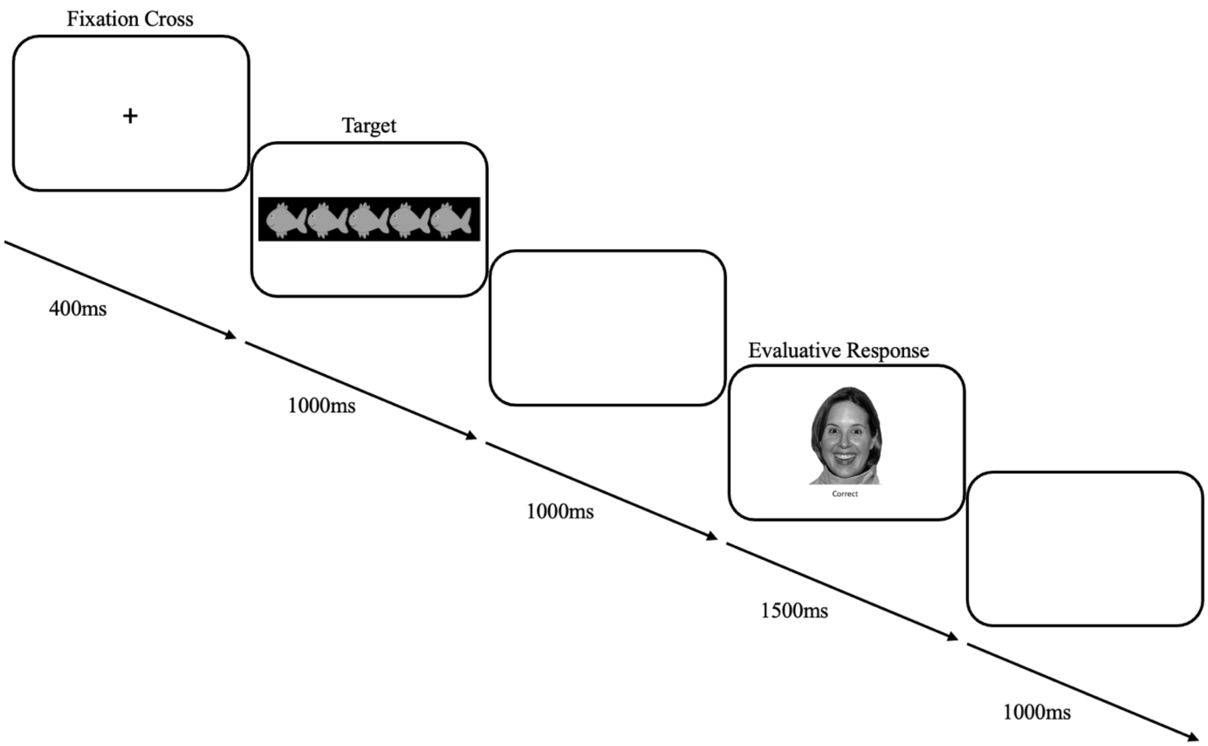


Figure 2
Modified Flanker Task (Brooker and Buss, 2014)



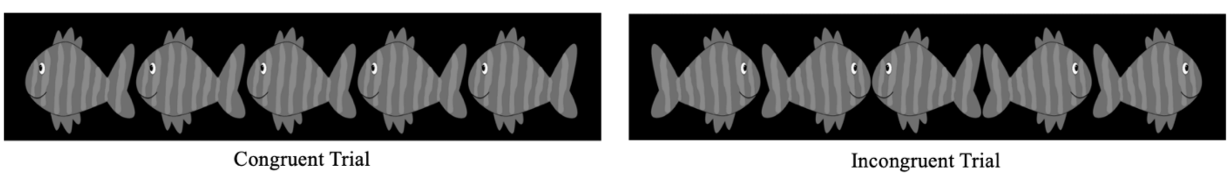
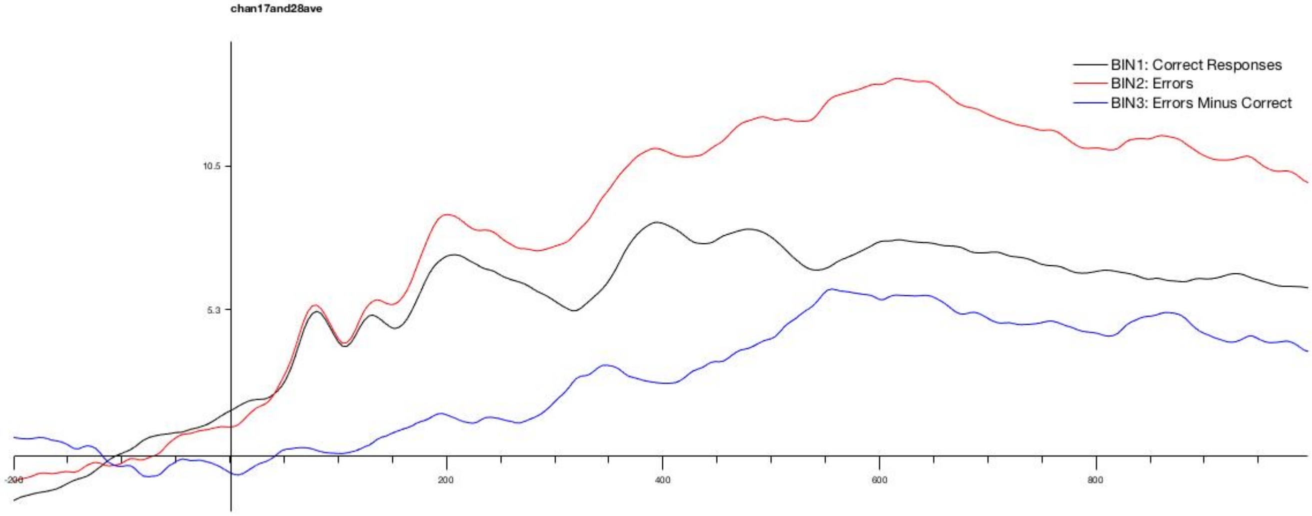


Figure 3

ERN Grand Average Waveform



Note: This waveform does not include the 2 participants that were recorded with a 64-channel net.