



Frontal alpha asymmetry in anxious school-aged children during completion of a threat identification task

Shane Wise ^{*},¹, Cynthia Huang-Pollock, Koraly Pérez-Edgar

The Pennsylvania State University, Department of Psychology, USA

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ABSTRACT

Asymmetry of EEG alpha power in the frontal lobe has been extensively studied over the past 30 years as a potential marker of emotion and motivational state. However, most studies rely on time consuming manipulations in which participants are placed in anxiety-provoking situations. Relatively fewer studies have examined alpha asymmetry in response to briefly presented emotionally evocative stimuli. If alpha asymmetry can be evoked in those situations, it would open up greater methodological possibilities for examining task-driven changes in neural activation. Seventy-seven children, aged 8–12 years old (36 of whom were high anxious), completed three different threat identification tasks (faces, images, and words) while EEG signal was recorded. Alpha power was segmented and compared across trials in which participants viewed threatening vs. neutral stimuli. Threatening images and faces, but not words, induced lower right vs. left alpha power (greater right asymmetry) that was not present when viewing neutral images or faces. Mixed results are reported for the effect of anxiety symptomatology on asymmetry. In a similar manner to studies of state- and trait-level withdrawal in adults, frontal neural asymmetry can be induced in school-aged children using presentation of brief emotional stimuli.

1. Introduction

Understanding the neural foundation of emotion is critical to better understanding, diagnosing, and treating psychological disorders (Insel & Cuthbert, 2015). Due to its superior temporal resolution, a considerable body of research has used electroencephalographic (EEG) measures which are capable of capturing moment to moment fluctuations in emotion processing. Of the techniques available to analyze EEG data, decomposing the signal into distinct frequency bands is particularly useful in approximating overall regional activity. Alpha power in older children and adults occurs in the 8–13 Hz frequency domain and is thought to be inversely related with neural activity, in which increased alpha power reflects decreased local neural activity (Cook, O'Hara, Uijtdehaage, Mandelkern, & Leuchter, 1998; Davidson, Chapman, Chapman, & Henriques, 1990).

Historically, asymmetry in alpha power in the right vs. left frontal lobes has been associated with a variety of emotional and motivational processes (Coan & Allen, 2003; Harmon-Jones, Gable, & Peterson,

2010). For example, relatively lower *right* alpha power (greater right neural activity) is associated with dispositional negative affect (Hagemann et al., 1999), clinical depression (Thibodeau, Jorgensen, & Kim, 2006), trait and clinical anxiety (Heller, Nitschke, Etienne, & Miller, 1997; Thibodeau et al., 2006), social inhibition (Fox et al., 1995), and increased cortisol levels (Buss et al., 2003). In contrast, relatively lower *left* alpha power (greater left neural activity) is correlated with greater dispositional positive affect (Harmon-Jones et al., 2010; Tomarken, Davidson, Wheeler, & Doss, 1992) as well as a tendency to experience impulsivity and anger (Gable, Mechin, Hicks, & Adams, 2015; Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997; Wacker, Heldmann, & Stemmler, 2003).²

Although some effects have failed to replicate (Meyer et al., 2015; Quinn et al., 2014; Hagemann et al., 1998; Reid, Duke, & Allen, 1998), this body of work has led to the development of the “motivational valence theory” suggesting that left frontal neural asymmetry is associated with an individual's trait-level approach orientation, while right frontal neural asymmetry is associated with a withdrawal orientation

* Corresponding author.

E-mail address: smw66@psu.edu (S. Wise).

¹ <https://orcid.org/0000-0002-2120-8818>

² The literature is mixed with respect to using power or activity in describing asymmetry patterns. For the sake of clarity, we will focus on alpha power, the specific metric captured with EEG, with the understanding that lower relative right alpha power (vs. left power) is indicative of greater right neural asymmetry.

(Davidson, Ekman, Saron, Senulis, & Friesen, 1990; Davidson, Jackson, & Kalin, 2000; Harmon-Jones & Gable, 2018). Although this theory has helped shape the field's understanding of the neural markers of emotional traits, the acknowledgment that emotion and motivation are dynamic processes (Coan & Allen, 2003) has more recently shifted work to determine whether state-level manipulations also influence EEG asymmetry (Harmon-Jones & Gable, 2018). Studies utilizing directed facial action (DFA; Levenson, Ekman, & Friesen, 1990), a common state-level manipulation in which participants make specific emotion facial expressions, have found that making angry and happy faces leads to left frontal neural asymmetry, while making sad and fearful faces does not (Stewart, 2014). Other emotion induction paradigms have also supported a state-level application of motivational valence theory, finding that inducing discrete periods of stress via fear of shock (Goodman, Rietschel, Lo, Costanzo, & Hatfield, 2013) or giving a speech (Pérez-Edgar, Kujawa, Nelson, Cole, & Zapp, 2013) can also induce shifts in alpha asymmetry.

In real life, emotional elicitation can occur on a much more rapid time scale than is typical for EEG emotion induction paradigms, which tend to average power across large segments of time (e.g., 1000 ms vs. 2 min; Davidson, et al., 1990; Smith, Reznik, Stewart, & Allen, 2017). If frontal alpha asymmetry reflects motivational approach at both state and trait levels, then it should also be possible to observe fluctuations in asymmetry on smaller, trial-by-trial time scales often seen in computer-based tasks. These tasks, such as the dot-probe and emotional Stroop, are often used to capture behavioral evidence for anxious responses to stimuli that are presented for < 2000 ms (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & Van Ijzendoorn, 2007; Dudeney, Sharpe, & Hunt, 2015; Puliafico & Kendall, 2006). If changes in alpha power can be reliably invoked on smaller time scales such as these, it may provide additional evidence alpha power asymmetry reflects early processing of motivationally relevant stimuli. Indeed, one study found changes in alpha asymmetry in response to threatening versus neutral stimuli in an emotional Stroop task in adults (Avram, Balteş, Miclea, & Miu, 2010). Pragmatically, children have more difficulty remaining still during EEG recordings, increasing the risk of movement artifacts when relying on larger windows of time. If children's power activity could be recorded and analyzed on a trial-level basis, future research may be able to increase efficiency of data gathering during emotionally relevant tasks and contrast EEG activity across multiple conditions of interest.

The emotional Stroop and dot-probe tasks are two of the most widely used paradigms to study emotional processing, particularly attentional bias to threat, which is believed to be an important cognitive mechanism contributing to the development of anxiety disorders (Bar-Haim et al., 2007; Dudeney et al., 2015; Puliafico & Kendall, 2006). However, a growing body of work has identified concerns with the psychometric properties and construct validity of these tasks (Algom, Chajut, & Lev, 2004; Kappenman, Farrens, Luck, & Proudfit, 2014; Rodebaugh et al., 2016; Wise, Huang-Pollock, & Pérez-Edgar, 2021). More recent work has suggested that adopting tasks in which bias can be directly measured during a decision process may be a more appropriate method to index behavioral (and by extension, neural) responses to threatening stimuli (MacLeod, Grafton, & Notebaert, 2019). These simpler threat identification paradigms have been successful in identifying differential emotional processing of threatening vs neutral stimuli. Anxious participants process threatening words more quickly (White, Ratcliff, Vasey, & McKoon, 2010), have a lower threshold to consider words threatening, and exhibit a greater expectation that words will be threatening (White, Skokin, Carlos, & Weaver, 2016). Similarly, participants who listened to negative music demonstrate enhanced attention to threatening words compared to those who listened to positive or no music (Sereno, Scott, Yao, Thaden, & O'Donnell, 2015).

Individuals with anxiety disorders represent an ideal population in which to assess the effectiveness of threat identification tasks in eliciting EEG alpha asymmetry. Anxiety disorders appear early in life, and the early elementary school years are the most common age for anxiety

disorders to be identified because sufficient time has elapsed to allow behavioral, academic, and social impairment to emerge (Rapee, Schniering, & Hudson, 2009; Van Ameringen, Mancini, & Furvolden, 2003; Woodward & Fergusson, 2001). Also, as children age, their capacity to discriminate threat cues matures (Lau et al., 2011; Pine, Helfinstein, Bar-Haim, Nelson, & Fox, 2009) and their tendency to attend to threatening cues increases dramatically (Britton, Lissek, Grillon, Norcross, & Pine, 2011; Lau & Waters, 2017; Pine, 2007). However, despite the developmental relevance of anxiety, the vast majority of the work studying trait level anxiety and EEG alpha asymmetry has been conducted with adults (Coan & Allen, 2003; Harmon-Jones et al., 2010; Jesulola, Sharpley, Bitsika, Agnew, & Wilson, 2015; Mathersul, Williams, Hopkinson, & Kemp, 2008; Perone, Gartstein, & Anderson, 2020), and no studies have analyzed state-based experimental manipulations of EEG alpha asymmetry in school-aged children. Doing so would help the field better understand how state-based neurobiological responses to threat are manifest in children with high trait anxiety, and would in turn help fill a gap in our understanding of the neural circuitry of childhood anxiety disorders.

The present study aims to set an initial foundation for this approach by exploring whether changes in frontal EEG alpha power can be experimentally manipulated on a brief (1 s) trial-by-trial level in school-aged children during threat classification tasks using different types of visual and text stimuli. If short term alterations in alpha asymmetry can be experimentally elicited to threat, it would indicate that not only is right asymmetry a neural signature found among trait-anxious children, but that it can also be invoked experimentally. This would allow the field to utilize a wider variety of tasks to compare different hemisphere-specific power responses to quickly appearing stimuli in school-aged children.

Hypothesis 1. Consistent with existing research, participants high in anxiety are expected to demonstrate lower right frontal EEG alpha power relative to left frontal (i.e., greater right neural asymmetry) than non-anxious participants.

Hypothesis 2. If alpha power asymmetry can be induced by brief changes (< 1 s) in state-level anxiety processing, viewing stimuli classified as threatening will result in relatively lower right frontal EEG alpha power (i.e., greater right neural asymmetry) relative to non-threatening stimuli.

2. Methods

2.1. Participants

Eighty-one children were recruited as part of a larger study on neurocognitive correlates of psychopathology in school-aged children. Children were recruited via a community-based sampling strategy to avoid well-known selection biases that occur when clinic-based recruitment is utilized (e.g., Cohen & Cohen, 1984; Goodman et al., 1997). Recruitment occurred via the FIRSt Families database, a database of families who are interested in participating in research at the Pennsylvania State University, through internet ads and posted public flyers, and through flyers distributed to local schools in Central Pennsylvania advertising for children with or without difficulties with anxiety or inattention. Exclusion criteria included: (1) current non-stimulant medication treatment (e.g., neuroleptics or antidepressants), (2) diagnosis of pervasive developmental disorder, intellectual disability, sensorimotor disability, psychosis, or other parent-reported neurological disorder, and (3) estimated Full Scale IQ (FSIQ) < 80. Four participants were removed due to insufficient (<30 trials per condition) usable data on each task, so the final sample consisted of seventy-seven children (41 girls) ages 8–12 years old ($M = 9.40$, $SD = 1.17$).

Common childhood disorders, such as attention deficit hyperactivity disorder, anxiety disorders, depressive/mood disorders, oppositional defiant disorder, and conduct disorder were assessed at a preliminary

visit using parent report on the Diagnostic Interview Schedule for Children, 4th Edition (DISC-IV; Shaffer et al., 1997) and the Behavioral Assessment System for Children, 3rd edition (BASC-3; Reynolds & Kamphaus, 2015). The BASC-3 is an age normed standardized rating form that measures both adaptive and problematic behaviors in children. Internal consistency ranges from .79–0.92 on the clinical scales, and test-retest correlations of these scales at an average of 22.2 days range from .65–0.92 (BASC-3; Reynolds & Kamphaus, 2015). In our sample, the internal reliability of the anxiety subscale was .93. The presence of psychopathology was not exclusionary; recruitment materials and provision of clinical feedback were intended to recruit parents of children who were concerned with anxiety or inattention. The sample included eight participants receiving full diagnoses of Generalized Anxiety Disorder on the DISC-IV. There were 24 additional children who scored above the clinical cutoff (t -score > 60 , 85th percentile) on the parent-rated BASC-3, but who did not meet full clinical criteria. Participants who either met full DSM-V criteria for an anxiety disorder or scored above the BASC-3 clinical cutoff were grouped into a high anxious ($n = 36$; BASC-3 $M = 69.72$; $SD = 7.98$; Range = 60–99) vs. non-anxious control ($n = 41$; BASC-3 $M = 47.24$; $SD = 7.34$; Range = 33–59) group. As would be expected given the ubiquity of comorbidity among childhood mental health disorders (Fisher, 2022), children in the high anxious group also scored higher on BASC-3 scores for depression ($F(1, 75) = 64.89, p < .001$), hyperactivity ($F(1, 75) = 5.80, p = .02$), inattention ($F(1, 75) = 4.98, p = .03$), and aggression ($F(1, 75) = 7.69, p = .01$). Table 1 provides sample demographics.

A post hoc power analyses was conducted in GPOWER (Faul et al., 2007) assuming $\alpha = 0.05$, $N = 77$, and $f = 0.25$ for main effects and interactions. With these assumptions, power was 0.68, 0.99, and 0.99 to detect the main effects of anxiety, within-subjects effects, and the 2-way interactions respectively. Power was 0.80 to detect an $f = 0.29$ for anxiety; an $f = 0.13$ for the main effects of Blur, Threat, and Hemisphere; an $f = 0.10$ for the main effect of Location; and an $f = 0.06$ for interactions.

2.2. Procedures

Informed written consent from parents and verbal assent from children were obtained prior to participation. Parents were given \$100 and provided relevant clinical feedback. Children were given a small prize. Participants attended two sessions in the larger study. The first visit included the administration of the DISC-IV and a comprehensive assessment battery including a 4-subtest WISC-IV IQ screener. During the second visit, children completed the following paradigms while the electroencephalogram (EEG) was captured. Task order was counterbalanced to reduce the practice effects.

Table 1
Participant demographics. Means with SD in parentheses.

	Control	Anxious	Total
N	41	36	77
Female	20, 48.8 %	21, 58.3 %	41, 53.2 %
Age	9.44 (1.21)	9.36 (1.15)	9.40 (1.17)
IQ	103.85 (11.91)	106.34 (14.22)	105.16 (13.03)
BASC Anxiety t-score	47.24 (7.34)	69.72 (7.98)	57.74 (13.61)
BASC Hyperactivity t-Score	52.17 (12.61)	59.00 (12.19)	55.36 (12.80)
BASC Inattention t-Score	54.00 (11.41)	59.53 (10.15)	56.58 (11.12)
BASC Aggression t-Score	51.02 (11.02)	58.75 (13.41)	54.64 (12.72)
BASC Conduct Disorder t-Score	51.41 (11.47)	55.22 (12.48)	53.19 (12.03)
BASC Depression t-Score	48.88 (8.21)	68.81 (13.20)	58.19 (14.69)
Asian/Pacific Islander	0, 0 %	1, 2.8 %	1, 1.3 %
Hispanic	4, 9.8 %	1, 2.8 %	5, 6.5 %
White	36, 87.8 %	33, 91.7 %	69, 89.6 %
Mixed Race	1, 2.4 %	1, 2.8 %	2, 2.6 %

2.3. Threat indexing tasks

Children completed three separate emotion identification tasks in counterbalanced order with a ~3-minute break between tasks. In each task, participants were shown a fixation cross for 500 ms, followed by either a neutral or a threatening stimulus for 1000 ms, followed by a prompt to answer via button box whether the presented stimulus was “scary” or “not scary”. The prompt remained on the screen for 2000 ms or until the participant responded. Each task involved 200 trials and took approximately 7–10 min total.

In the “Images” task, the stimuli were photographs of various neutral and threatening items (e.g., box of tissues, knife) or scenarios (e.g., person eating ice cream, tornado) collected from the IAPS dataset (Lang, 2005). In the “Faces” task, the stimuli were neutral and angry faces collected from the NimStim (Tottenham et al., 2009) and KDEF (Lundqvist, 1998) datasets. In both the Images and Faces tasks, each image was presented twice – once in its normal resolution and once blurred. This was done to increase difficulty and ensure appropriate effort, but there were no specific hypotheses related to this manipulation on EEG power asymmetry. Images were blurred by applying the speckle function in the Opencv2 package in Python.

In the “Words” task, the stimuli consisted of 200 words developed in-house based on the Fry list (Fry, 2000). The authors reviewed the considered word stimuli and agreed upon valence (threatening or neutral) for each. Half of the chosen words were thus rated as threatening, while half were rated as neutral. There was no blurring procedure for this task.

See Supplemental Tables 1–3 for a list of stimuli from each task, along with that stimulus’s valence status (Threat or Neutral). Participants answered “accurately” (in line with the pre-determined valence), on 71.3% of Faces trials, 81.8% of Images trials, and on 74.4% of Words trials.

2.4. EEG asymmetry

EEG data was collected continuously using a 32-channel passive electrode BrainVision cap and a BrainAmp amplifier. Vertical eye movements were monitored by an electrode 1 cm below the left eye, while horizontal eye movements were monitored by electrodes 1 cm to the outside of each eye. All impedances were kept below 20 k Ω . Electrodes were referenced to Cz during collection and re-referenced to the average of the left and right mastoid during pre-processing. Power was recorded at a 1000 Hz sampling rate starting 100 ms before stimulus onset through 1000 ms after stimulus onset, to allow for a 100 ms baseline correction. Brain Vision Analyzer (Brain Products GmbH, Germany) was used to pre-process and process the data (GmbH, 2019). A high-pass frequency of 0.1 Hz and a low pass frequency of 40 Hz were used to filter the data. Eye movement artifacts were removed using the Gratton method (Gratton, Coles, & Donchin, 1983). Visual inspection was conducted to detect and remove bad channels, and an automatic artifact detection process was applied which removed trials containing a voltage step $> 100 \mu\text{V/ms}$, absolute difference $> 300 \mu\text{V/ms}$, or amplitude outside of -200 – $200 \mu\text{V}$ for any electrode. Electrodes containing $> 35\%$ bad data were removed from analysis and the data was re-processed. Following this processing, any trial condition (e.g., Non-Blurred Threat images) for any participant containing fewer than 30 usable trials was not included in analyses, resulting in the removal of this data for 4 participants in the Faces task, 2 in the Images task, and 0 in the Words task. This process resulted in an average of 177.31 usable trials per participant per task. Trial numbers per condition are presented in Supplemental table 4.

Power was computed using a Fast Fourier Transformation with a 50% Hamming window, alpha power was output at 8–13 Hz, and segments were calculated based on trial condition. We examined the homologous frontal electrode pairs F3/F4, F7/F8, FP1/FP2, FC1/FC2, and FC5/FC6. Values were log transformed. There were no hypotheses

regarding which electrode site(s) would be the most relevant to this task; previous research has found asymmetry at a variety of different frontal sites (Reznik & Allen, 2018). See supplemental Fig. 1 for topographical maps of alpha power distribution during each task.

3. Results

Substantive results in all three tasks did not change when only “correct” trials were included or when parent-report BASC-3 T-Score was used as a dimensional indicator of anxiety, as opposed to dichotomous anxious groups. Therefore, results below are reported using all trials and without the dimensional covariate unless otherwise noted.

3.1. Faces task

Within-subjects factors included Hemisphere (2: left, right), electrode pair Location (5: FP1/FP2, F3/F4, F7/F8, FC1/FC2, FC5/FC6), Threat (2: threat, neutral), and Blur (3: blur, non-blurred). Table 2 contains the results of the initial 5-way GLM. There was no main effect of Blur, Threat, Hemisphere, or Anxiety (all $p > .20$), but there was a main effect of electrode pair Location ($F(4, 272) = 9.83, p < .001$). This main effect was qualified by a significant 2-way Hemisphere x Location interaction, ($F(4, 272) = 5.78, p < .001$) as well as a significant 3-way Hemisphere x Threat x Location interaction ($F(4, 272) = 6.20, p < .001$).

Post hoc analyses decomposing the 3-way interaction found a significant Hemisphere x Threat interaction at FP1/FP2 ($F(1, 69) = 5.69, p = .02$) and F7/F8 ($F(1, 69) = 13.20, p = .001$; Fig. 1). This 2-way interaction did not yield a significant main effect of side for either Threat or Neutral images at FP1/FP2 (both $p > .11$, both $\eta^2 < 0.04$). However, there was a main effect of Hemisphere for Threat faces at F7/F8 ($F(1, 69) = 10.94, p = .002$) in which alpha power was lower in the right than left hemisphere (i.e., right frontal asymmetry). There was no effect of Hemisphere for Neutral images at either location (both $p > .08$, both $\eta^2 < 0.04$).

The asymmetry when viewing Threat faces was driven by a higher alpha power value in the left hemisphere in response to Threat vs

Table 2

Faces Task 5-way GLM: 2(Anxiety Status) x 5 (Electrode Pair Location) x 2 (Threat) x 2 (Hemisphere) x 2 (Blur).

Within-Subjects Factor	df	F	p	η^2
Location	272	9.83	< 0.001 **	0.126
Blur	68	0.32	0.58	0.005
Threat	68	1.26	0.27	0.018
Hemisphere	68	1.68	0.20	0.024
Location x Blur	272	2.02	0.09	0.029
Location x Threat	272	1.56	0.19	0.022
Blur x Threat	68	0.23	0.63	0.003
Location x Blur x Threat	272	0.15	0.96	0.002
Location x Hemisphere	272	6.711	< 0.001 **	0.098
Blur x Hemisphere	68	1.04	0.31	0.015
Location x Blur x Hemisphere	272	1.54	0.19	0.022
Threat x Hemisphere	68	1.85	0.18	0.026
Location x Threat x Hemisphere	272	6.2	< 0.001 **	0.08
Blur x Threat x Hemisphere	68	0.23	0.63	0.003
Location x Blur x Threat x Hemisphere	272	0.4	0.81	0.006
Between-Subjects Factor	df	F	p	η^2
Anxiety	68	0.6	0.44	0.009
Location x Anx	272	0.69	0.59	0.01
Blur x Anx	68	1.38	0.24	0.02
Threat x Anx	68	< 0.01	0.99	< 0.001
Hemisphere x Anx	68	0.16	0.69	0.002
Location x Blur x Anx	272	0.89	0.47	0.013
Location x Threat x Anx	272	0.21	0.93	0.003
Blur x Threat x Anx	68	1.18	0.28	0.017
Location x Blur x Threat x Anx	272	0.68	0.61	0.01
Location x Hemisphere x Anx	272	0.97	0.42	0.014
Blur x Hemisphere x Anx	68	0.04	0.85	0.001
Location x Blur x Hemisphere x Anx	272	0.98	0.42	0.014
Threat x Hemisphere x Anx	68	0.11	0.74	0.002
Location x Threat x Hemisphere x Anx	272	0.9	0.47	0.013
Blur x Threat x Hemisphere x Anx	68	3.62	0.06	0.051
Location x Blur x Threat x Hemisphere x Anx	272	1.93	0.11	0.028

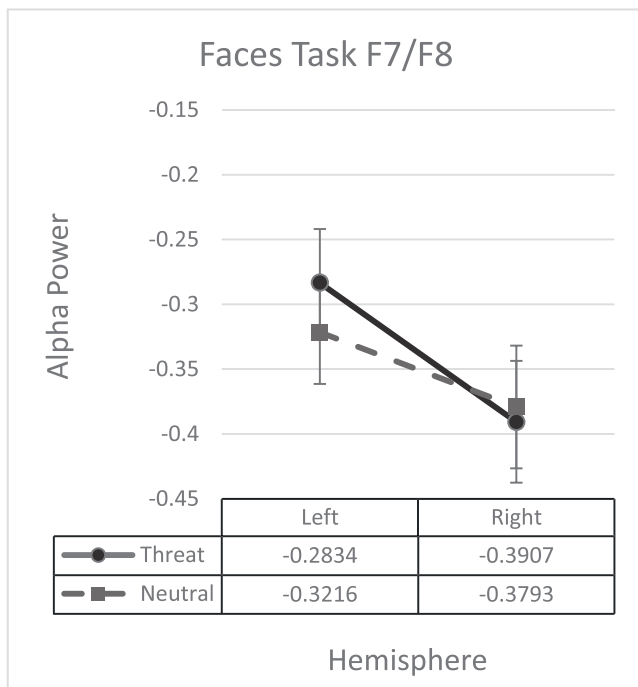
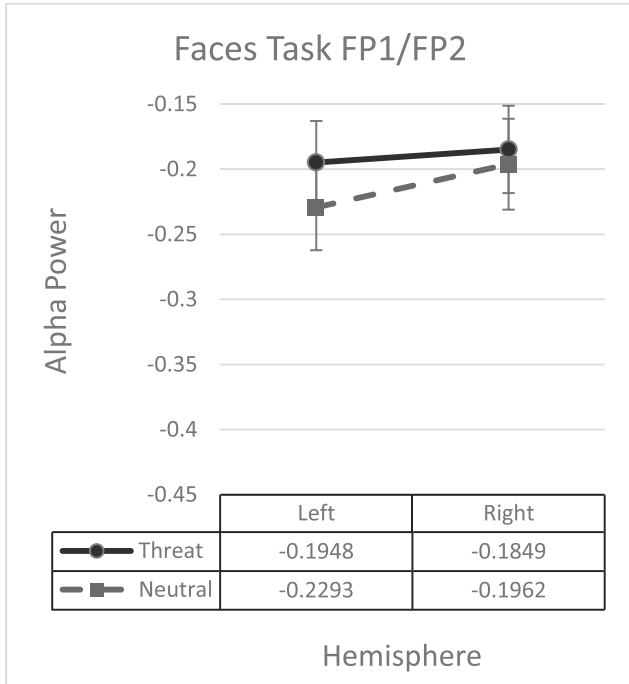


Fig. 1. Alpha power values in each hemisphere at the FP1/FP2 and F7/F8 site pairs while participants viewed Threatening vs Neutral faces. Error bars represent standard error. Because alpha power is inversely related to neural activity, greater right alpha power here represents less right neural activity and vice versa. Right frontal asymmetry is indicated by less power in the right hemisphere vs. left hemisphere.

Neutral faces ($F(1, 72) = 7.22, p = .01$). There was no difference in alpha power value in the right hemisphere between Threat vs Neutral images ($F(1, 72) = 1.19, p = .28$). Thus, threatening faces elicited greater alpha power in the left frontal hemisphere without a decrease in right alpha power, in contrast to the expected finding of a decrease in right alpha power with no changes in the left.

Because the expected main effect of anxiety on alpha power was not observed in the GLMs, we evaluated this hypothesis dimensionally in a post-hoc correlation analysis. There was a significant negative correlation between parent-reported BASC-3 anxiety and the asymmetry score (i.e. right alpha power – left alpha power) at the F3/F4 site ($r = -0.29, p = .01$). With increasing anxiety, participants showed lower alpha power asymmetry scores (i.e., greater right EEG asymmetry) for both threat ($r = -0.25, p = .03$) and neutral ($r = -0.32, p = .001$) stimuli, indicating that this effect was not dependent on stimulus content. The anxiety-asymmetry correlation was not significant at any other site (all $r < 0.14$, all $p > .24$).

Thus, when anxiety was evaluated as a categorical variable, no group differences in asymmetry/power were observed, but when anxiety was evaluated dimensionally, it predicted greater right EEG asymmetry as expected at the F3/F4 site.

3.2. Images Task

Table 3 contains the results of the initial 5-way GLM. This model indicated a main effect of electrode pair location ($F(4, 272) = 14.21, p < .001$), Blur ($F(1, 68) = 13.99, p < .001$), and Threat ($F(1, 68) = 11.84, p < .001$), but not Hemisphere ($F(1, 68) = 0.72, p = .39$) or Anxiety ($F(1, 68) = 1.22, p = .27$). There was a significant two-way interaction of Location x Hemisphere ($F(4, 272) = 6.84, p < .001$), a significant three-way interaction of Location x Threat x Hemisphere ($F(4, 272) = 5.95, p < .001$), and a significant four-way interaction of

Table 3
Images Task 5-way GLM: 2(Anxiety Status) x 5 (Electrode Pair Location) x 2 (Threat) x 2 (Hemisphere) x 2 (Blur).

Within-Subjects Factor	df	F	p	η ²
Location	272	14.21	< 0.001 **	0.173
Blur	68	13.99	< 0.001 **	0.171
Threat	68	11.84	0.001 **	0.148
Hemisphere	68	0.72	0.39	0.01
Location x Blur	272	0.59	0.67	0.009
Location x Threat	272	0.76	0.55	0.011
Blur x Threat	68	0.72	0.40	0.01
Location x Blur x Threat	272	2.12	0.08	0.03
Location x Hemisphere	272	6.84	< 0.001 **	0.09
Blur x Hemisphere	68	0.06	0.81	0.001
Location x Blur x Hemisphere	272	1.09	0.36	0.016
Threat x Hemisphere	68	1.82	0.18	0.026
Location x Threat x Hemisphere	272	5.95	< 0.001 **	0.08
Blur x Threat x Hemisphere	68	0.79	0.38	0.012
Location x Blur x Threat x Hemisphere	272	2.2	0.07	0.031
Between-Subjects Factor	df	F	p	η ²
Anxiety	68	1.22	0.27	0.018
Location x Anx	272	1.59	0.18	0.023
Blur x Anx	68	0.01	0.93	0.001
Threat x Anx	68	3.23	0.08	0.045
Hemisphere x Anx	68	0.08	0.78	0.001
Location x Blur x Anx	272	1.04	0.39	0.015
Location x Threat x Anx	272	0.69	0.60	0.01
Blur x Threat x Anx	68	0.01	0.94	0.001
Location x Blur x Threat x Anx	272	0.26	0.90	0.004
Location x Hemisphere x Anx	272	1.23	0.29	0.018
Blur x Hemisphere x Anx	68	6.49	0.01 *	0.087
Location x Blur x Hemisphere x Anx	272	1.3	0.27	0.019
Threat x Hemisphere x Anx	68	0.04	0.84	0.001
Location x Threat x Hemisphere x Anx	272	2.63	0.04	0.037
Blur x Threat x Hemisphere x Anx	68	0.22	0.64	0.003
Location x Blur x Threat x Hemisphere x Anx	272	0.97	0.42	0.014

Location x Threat x Hemisphere x Anxiety ($F(4, 272) = 2.63, p = .04$). A 3-way interaction of Blur x Hemisphere x Anxiety was also observed ($F(1, 68) = 6.49, p = .01$). However, post-hoc analysis of that interaction found no main effect of Hemisphere or Anxiety, nor a significant Hemisphere x Anxiety interaction for blurred or non-blurred images (all $p > .28$, all $\eta^2 < 0.02$).

Post-hoc analyses of the four-way Location x Threat x Hemisphere x Anxiety interaction found no significant Hemisphere x Threat x Anxiety interaction at any Location (all $p > .13$, all $\eta^2 < 0.03$), but the Location x Threat x Hemisphere interaction was significant for both anxious ($F(4, 124) = 5.86, p < .001$) and non-anxious ($F(4, 148) = 2.86, p = .03$) participants.

Further decomposition of this 3-way interaction revealed a significant Hemisphere x Threat interaction at F7/F8 ($F(1, 68) = 6.44, p = .01$) and FC5/FC6 ($F(1, 68) = 6.31, p = .01$; Fig. 2). As with the Faces task, visual inspection and additional follow-up analyses found lower alpha power on the right vs. left hemisphere (i.e., right EEG asymmetry) at both the F7/F8 site ($F(1, 68) = 15.63, p < .001$) and the FC5/FC6 site ($F(1, 68) = 6.86, p = .001$) when participants viewed Threatening, but not Neutral (both $p > .18$, both $\eta^2 < 0.02$) images.

Again, this asymmetry when viewing Threat images was driven by an increase in alpha power in the left hemisphere at both the F7/F8 site ($F(1, 68) = 13.84, p < .001$) and the FC5/FC6 site ($F(1, 68) = 4.51, p = .04$). Alpha power in the right hemisphere did not differ by Threat vs. Neutral images (both $p > .37$, both $\eta^2 < 0.01$). Thus, the observed right frontal EEG asymmetry was driven by task-related modulation of power in the left hemisphere.

As with the Faces task, we evaluated the anxiety-asymmetry hypothesis dimensionally in a post-hoc correlation analysis. There was again a significant negative correlation between parent-reported BASC-3 anxiety and the asymmetry score (i.e. right alpha power – left alpha power) at the F3/F4 site ($r = -0.27, p = .02$). With increasing anxiety, participants showed lower alpha power asymmetry scores (i.e., greater right EEG asymmetry) for both threat ($r = -0.26, p = .03$) and neutral ($r = -0.27, p = .02$) stimuli, indicating that this effect was not dependent on stimulus content. The anxiety-asymmetry correlation was not significant at any other site (all $r < 0.19$, all $p > .09$).

3.3. Words task

Stimuli in the Words task were not blurred, so there was one less term. The initial 4-way GLM indicated no significant main effects of Threat ($F(1, 68) = 0.04, p = .85$), Hemisphere ($F(1, 68) < 0.01, p = .99$), or Anxiety ($F(1, 68) = 0.60, p = .44$). There was a main effect of Location ($F(4, 272) = 11.11, p < .001$) which was qualified by a 2-way Location x Hemisphere interaction ($F(4, 272) = 7.08, p < .001$). Decomposition of this interaction revealed a significant main effect of Hemisphere at F3/F4 ($F(1, 69) = 16.14, p < .001$) and F7/F8 ($F(1, 69) = 9.12, p = .004$) sites (Fig. 3). Left EEG asymmetry was evident at the F3/F4 site pair, but right EEG asymmetry at the F7/F8 site pair.

We again assessed the correlation of parent-reported anxiety symptomatology with asymmetry as a post-hoc analysis. The correlation was not significant at any site in this task (all $r < 0.21$, all $p > .08$).

4. Discussion

Lateralized frontal cortical activity is thought to reflect the formation of approach and withdrawal motivational states (Harmon-Jones & Gable, 2018). Foundational research in this field has shown that right neural asymmetry is associated with trait-level anxiety and with withdrawal motivation both at baseline and during prolonged anxious states (Coan, Allen, & McKnight, 2006; Davidson, Ekman, et al., 1990; Reznik & Allen, 2018; Thibodeau et al., 2006). However, relatively little research has analyzed rapid changes to alpha activity during emotionally relevant laboratory tasks. Anxious adults have been shown to exhibit right neural asymmetry in response to fearful faces in an

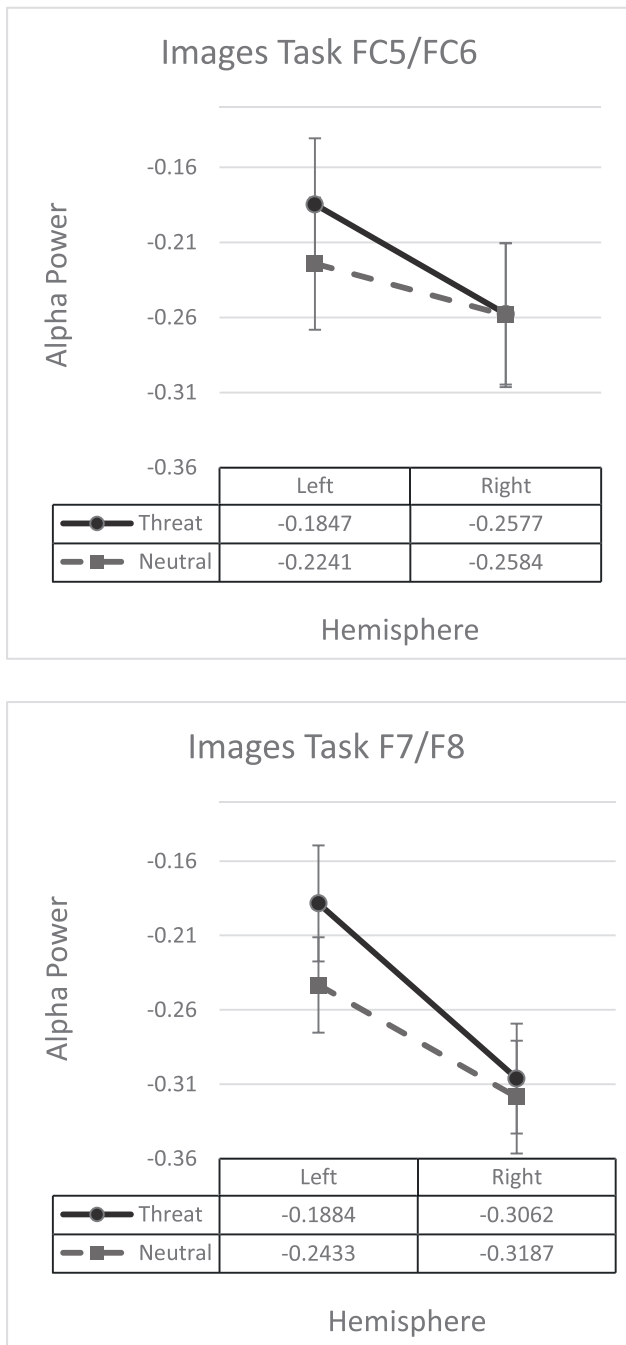


Fig. 2. Alpha power values in each hemisphere at the FC5/FC6 and F7/F8 site pairs while participants viewed Threatening vs Neutral images. Error bars represent standard error. Because alpha power is inversely related to neural activity, greater right alpha power here represents less right neural activity and vice versa. Right frontal asymmetry is indicated by less power in the right hemisphere vs. left hemisphere.

emotional Stroop task (Avram et al., 2010), but to our knowledge, no such study has examined neural activation via alpha power in response to emotionally evocative stimuli in children.

The present study employed several different variants of a threat identification task in a sample of school-aged children. Frontal asymmetry was present for threatening stimuli in two of our three tasks. Threatening faces resulted in right asymmetry at the F7/F8 electrode site, while neutral faces did not. Threatening, but not neutral, IAPS images similarly resulted in a right asymmetry at the F7/F8 and FC5/FC6 sites. At each site for both tasks, this asymmetry was the result of

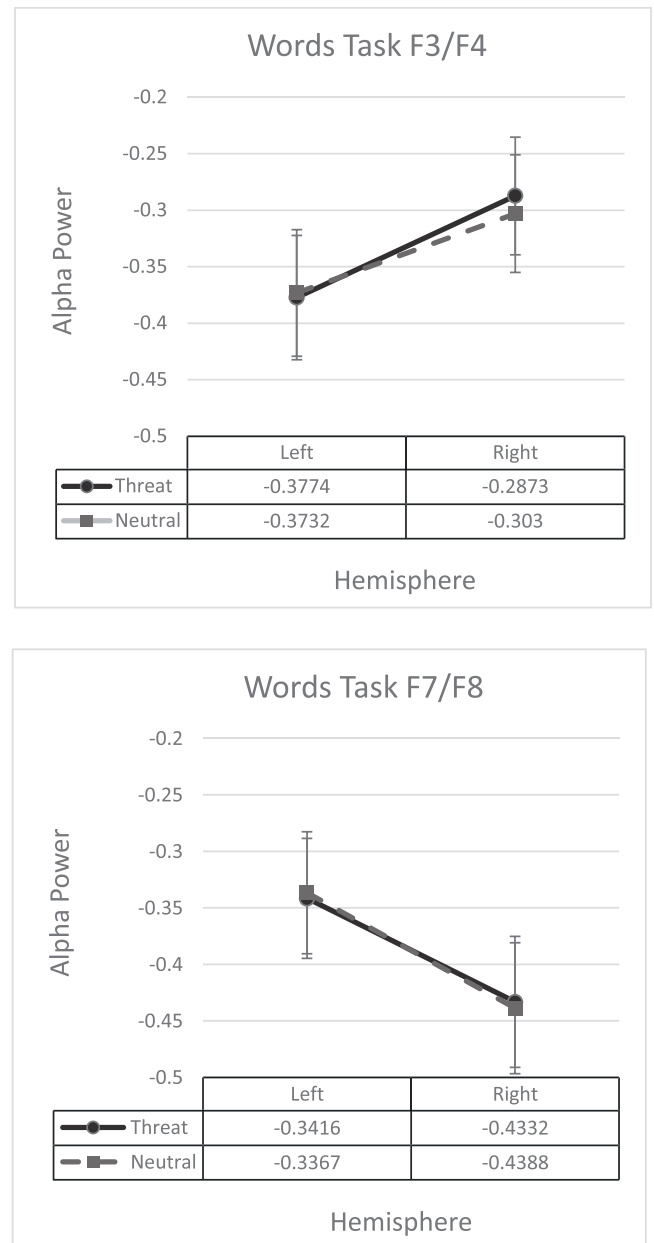


Fig. 3. Alpha power values in each hemisphere at the F3/F4 and F7/F8 site pairs while participants viewed Threatening vs Neutral words. Error bars represent standard error. Because alpha power is inversely related to neural activity, greater right alpha power here represents greater right neural activity and vice versa. Right frontal asymmetry is indicated by less power in the right hemisphere vs. left hemisphere.

threatening stimuli causing higher alpha power in the left hemisphere versus neutral stimuli, while power in the right hemisphere was the same for both trial types.

The general suggestion is that left neural activity is associated with approach motivation, while right neural activity is associated with withdrawal motivation (Harmon-Jones & Gable, 2018). In the current data, it appears that rather than threat potentiating activity in the right hemisphere (i.e., less EEG power), the threat stimuli suppressed left hemisphere activity (i.e., greater EEG power). Thus, while we saw the expected pattern of right frontal asymmetry, it was driven by modulations in the left hemisphere. Indeed, the left and right hemispheres work together to influence an individual's overall motivational valence, so it is wholly possible that activity in one hemisphere inhibits or influences

the functioning in the opposite, regardless of which hemisphere drives the asymmetry (Harmon-Jones et al., 2010). In adults, resting state and task-based studies have often found between-groups differences in the degree of overall alpha asymmetry (calculated as a difference score) that are either not accompanied by statistically significant differences in either of the individual hemispheres, or are due to differences in the non-hypothesized hemisphere (Coan & Allen, 2004; Harmon-Jones & Allen, 1997; Harmon-Jones & Gable, 2018). Although there is not yet an existing literature of task-based asymmetry in children, resting-state studies with pediatric samples commonly report only overall asymmetry values rather than hemisphere-specific power (e.g., Baving, Laucht, & Schmidt, 2002; Fox, Henderson, Rubin, Calkins, & Schmidt, 2001; Kentgen et al., 2000; Peltola et al., 2014), but see Goldstein et al. (2016) and Pérez-Edgar and Fox (2005). This in turn makes it difficult to determine whether left or right hemisphere power differences are responsible for the asymmetry, prompting some to suggest that hemispheric-specific effects should always be reported (Reznik & Allen, 2018). What is consistent across all studies is that relative hemispheric asymmetry appears to be the relevant neural metric of the approach/withdrawal spectrum in which greater right asymmetry for threatening images (regardless of which hemisphere is driving the effect) is associated with greater withdrawal.

Asymmetry towards threatening stimuli was not found in all tasks. The absence of asymmetry for words may simply reflect changes in task demand as a function of age. Adults and children require < 150 ms to identify faces and simple images (Johnson & Olshausen, 2005). However, neurological signals of word processing and recognition occur much later, particularly for children. In adults, the N170 Event Related Potential (ERP) is thought to represent the first step of word processing. In children, this waveform does not occur until 240 ms after stimulus onset. The final step of word reading, the referencing of an orthographic lexicon, appears 400 ms after stimulus onset in adults (Hasko, Groth, Bruder, Bartling, & Schulte-Körne, 2013). Where the N400 amplitude for familiar words is smaller in adults, indicating easier processing of semantic information (Braun et al., 2006), school-aged children exhibit equally high amplitudes for familiar and unfamiliar words, indicating that processing meaning, even of familiar words, is more effortful (Hasko et al., 2013). Thus, while children in the current study were able to begin processing affective information within 150 ms of face and image presentation, they likely did not form an understanding of the word information until at least 400 ms after stimulus presentation, leaving less time for alpha power to demonstrate changes. It is possible that there were truly no changes in alpha power during this task, but it may also be the case that differences would have been seen if the recording had been longer.

In the Words task, we did see a significant left asymmetry at F3/F4 and a significant right asymmetry at F7/F8. While not related to anxiety or threat, we believe that this overall asymmetry highlights that EEG activity is not uniform across the frontal lobe and emphasizes the importance of studying each electrode separately.

When evaluated dichotomously, a main effect of trait anxiety on alpha power asymmetry was not observed in any of the three tasks, but when anxiety was examined dimensionally, greater anxiety was associated with greater right frontal asymmetry as expected at F3/F4 in both the Faces and Images tasks. Relatively greater right asymmetry has been identified in anxious adults (Goodman et al., 2013; Thibodeau et al., 2006) and behaviorally inhibited young children (Pérez-Edgar & Fox, 2005; Poole & Schmidt, 2020). However, resting state asymmetry findings are inconsistent in school aged children (Baving et al., 2002; Demerdzieva & Pop-Jordanova, 2015). This is the first study in this age group to evaluate trait-based asymmetry during active task performance, and our findings suggest that this trait asymmetry persists even during active task engagement. However, this effect was found only at one out of five frontal sites (F3/F4). The GLM, which controls for the fact that multiple analyses were run, did not indicate a location by side by anxiety interaction. We recommend interpreting this finding with

caution, and it will be beneficial to replicate the finding that anxiety is correlated with asymmetry in school-aged children in the future. Unfortunately, resting state EEG recordings were not obtained in the current study, so it remains possible that further anxiety-related effects were present at baseline, but that such effects were washed out during active task performance, which requires increased bilateral neural activity, masking between-subjects differences in alpha power activation (Coan & Allen, 2003).

Previous asymmetry research has largely focused on the recording site pairs F3/F4 and F7/F8 (Harmon-Jones & Gable, 2018; Reznik & Allen, 2018). In the current study, the expected effect of relatively greater right asymmetry when viewing threatening stimuli was observed at F7/F8 for both the Faces and Images task, but not at F3/F4. However, frontal regions are highly heterogeneous and variable in their functionality (Pessoa, 2018), and EEG itself notably lacks spatial specificity (Smith et al., 2017), so it is not surprising to find some variation in electrode sites linked to alpha asymmetry. In the present study, we elected to analyze and report all available frontal sites because multiple frontal sites are believed to play a role in emotion and motivational formation (Allen, Coan, & Nazarian, 2004; Davidson, 2004; Demerdzieva & Pop-Jordanova, 2015; Papousek & Schulte, 2002) and the literature lacks a compelling a priori hypothesis on why one or two electrode sites are reported. That being said, the lack of stimulus-based findings at F3/F4 in our study could suggest that our paradigm does not elicit replicable frontal asymmetry.

There are several areas that warrant further study and consideration. First, although our paradigm was well suited to evaluating withdrawal motivation, it did not include positively valenced scenes or happy faces that would have allowed approach motivation to be indexed. Second, the motivational valence theory assumes that an individual's motivational or emotional state has been altered in a meaningful way by the experimental manipulation, and it would be difficult to argue that to be the case in the current study. That being said, simple manipulation of stimulus valence resulted in fluctuations of alpha asymmetry, suggesting that substantively altering current emotional state is not required. Analyses were conducted based on the empirical classification of images as threatening vs. non-threatening as opposed to how the children themselves classified the stimuli. Participants in the current study were reasonably "accurate" in their responses (i.e., indicating threatening stimuli were scary and neutral stimuli were not); results did not change when substantive analyses were re-run using only "correct" trials.

Resting-state baseline is commonly used to detect between-subjects differences (Smith et al., 2017) and although neutral image trials could potentially be used as a stand-in for baseline activity, they in fact represent activation in response to image presentation. Thus, it is recommended that future research in children include both resting state and task conditions to determine baseline activity as well as activation in response to various emotion or motivation elicitation. However, it is worth noting that evidence suggests that school-aged children experience high levels of cognitive load during resting-state, and may require watching a low-engagement video to approximate true resting neural activity similar to that seen when adults and adolescents view a fixation cross (Camacho, Quiñones-Camacho, & Perlman, 2020; Greene, Black, & Schlaggar, 2016).

5. Conclusion

Over the last thirty years, a robust literature has examined hemispheric asymmetry of EEG alpha power in the frontal lobes to study the formation of approach and withdrawal motivation. This work has historically treated the approach/withdrawal spectrum as a trait, but research has more recently begun analyzing state changes in motivational valence as well. However, relatively little research has examined this process in school-aged children, despite comparable work with adults. The present study aimed to determine if viewing threatening images would result in short-term alterations in frontal asymmetry in a

sample of anxious and control children. Consistent with expectations, results indicated a right frontal neural asymmetry when viewing threatening images or faces, but not neutral images or faces. Findings for anxiety status were mixed but suggest that anxiety may also be linked with greater right neural asymmetry. Overall, these results suggest that, similar to adults, children experience asymmetry alterations in response to emotionally evocative stimuli in a manner consistent with the motivational valence theory, but that the association between anxiety and asymmetry is not straightforward in children.

Ethics approval

Study procedures were approved by the Institutional Review Board (IRB#32, 126) of The Pennsylvania State University. Families were compensated for their participation.

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Conflict of interests

There are no conflicts of interest to report for any author on the manuscript submission *Frontal Alpha Asymmetry in Anxious School-Aged Children During Completion of a Threat Identification Task*.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.biopsycho.2023.108550](https://doi.org/10.1016/j.biopsycho.2023.108550).

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