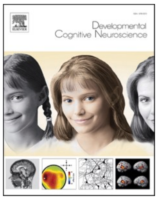
Developmental Cognitive Neuroscience 46 (2020) 100863

Contents lists available at ScienceDirect

Developmental Cognitive Neuroscience

journal homepage: www.elsevier.com/locate/dcn



A longitudinal study investigating trajectories of sensitivity to threat over time and their association with alpha asymmetry among children and adolescents

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ARTICLE INFO

Keywords:
EEG
Alpha asymmetry
Longitudinal
Sensitivity to threat
Children
Adolescent

ABSTRACT

Research has yet to investigate trajectories of sensitivity to threat across childhood and adolescence. Further, neural associations of these trajectories remain unknown. The current 3-year study used a latent class growth curve analysis to investigate whether there were distinct trajectories of sensitivity to threat among children and adolescents over time ($N = 363$; age range at Time $1 = 8$–14). We also examined whether alpha asymmetry (a neural index of motivational tendencies) was associated with the different trajectories. Results revealed three distinct trajectory groups (1) high-stable sensitivity to threat, (2) moderate-increasing sensitivity to threat and (3) low-stable sensitivity to threat. The high-stable sensitivity to threat group had greater right frontal asymmetry activation (i.e., greater neural avoidance motivation) than the other two groups. Additionally, females, those with higher parental education, and individuals with more advanced pubertal development (but not age) had greater odds of being part of the high-stable sensitivity to threat group compared to the other groups. Of interest, puberty rather than age may be an important indicator of heightened sensitivity to threat.

1. Introduction

According to Gray's original Reinforcement Sensitivity Theory (1970), motivation is driven by individual differences in sensitivity to reward and sensitivity to threat. Sensitivity to reward (SR; heightened responsiveness to reward/pleasure) and sensitivity to threat (ST; heightened responsiveness to threat), also called sensitivity to punishment, can help explain why individuals may be driven to engage in or avoid certain behaviors (see Corr, 2004; Corr et al., 2013). ST in children and adolescents may be a particularly important construct to examine, as the predisposition to avoid threat may be a risk factor in the development of anxiety (Degnan and Fox, 2007). Indeed, children and adolescents who are more sensitive to threat have a greater likelihood of developing anxiety compared to those who are less sensitive to threat (Balle et al., 2013; Bar-Haim et al., 2007; Johnson et al., 2003; Katz et al., 2020; Pérez-Edgar et al., 2010, 2011; Vervoort et al., 2010). Thus, investigating sensitivity to threat is critical in order to advance our understanding of the development of anxiety in youth.

1.1. Right frontal asymmetry and avoidance motivation

Avoidance motivation (i.e., the strong desire to avoid threats) is thought to be one of the core components of threat sensitivity (Gray, 1970; Gray and McNaughton, 2000). One way to measure avoidance motivation is right frontal asymmetry (neural activation associated with avoidance tendencies; Borod, 1992; Fox, 1991). There is a long line of research using electroencephalography (EEG) to measure cortical activation in the frontal hemispheres (see Briesemeister et al., 2013 for a review). This research has highlighted that right anterior cortical activity is a biological substrate of avoidance motivation, whereas left anterior cortical activity is a biological substrate of approach motivation (Thibodeau et al., 2006).

Evidence for this classification emerged from studies on individuals with brain damage (and animal research) whereby damage (or disruption) to the right versus left frontal hemispheres impacted emotion differentially (Silberman and Weingartner, 1986). Patients with damage to the right frontal hemisphere (i.e., greater activation in the left hemisphere) tended to express more euphoria and positive moods, whereas those with damage to the left frontal hemisphere (i.e., greater activation in the right hemisphere) expressed more negative/avoidant

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https://doi.org/10.1016/j.dcn.2020.100863
Received 18 December 2019; Received in revised form 10 August 2020; Accepted 27 August 2020

moods (Lipsey et al., 1983; Robinson et al., 1983, 1984; Sackeim, 1982). Given these findings, researchers became interested in individual differences in the asymmetry between the frontal hemispheres among non-brain damaged populations. Subsequent studies have confirmed that individuals in normative populations differ in their tendency to have greater right [versus left] or greater left [versus right] cortical activation (Henderson et al., 2004; Lopez-Duran et al., 2012; McManis et al., 2002).

Frontal asymmetry is measured using the alpha frequency band (8−13 hz). Alpha power is inversely related to cortical activity (Gevins et al., 1997); thus, *lower* levels of alpha power reflect greater cortical activation. To obtain a measure of frontal alpha asymmetry, researchers subtract alpha activation in the left anterior cortex from alpha activation in the right anterior cortex (Tomarken et al., 1992). This creates a continuous variable, with positive scores (greater right than left *alpha* activation) representing greater relative left cortical activation and negative scores (greater left than right *alpha* activation) representing greater relative right cortical activation. For clarity, in the present study we use the term 'right frontal asymmetry' to indicate frontal alpha asymmetry scores associated with avoidance tendencies [i.e., greater right (versus left) cortical activation].

1.2. *Threat sensitivity and frontal asymmetry*

Importantly, individuals with greater right frontal asymmetry should also self-report greater sensitivity to threat, given that avoidance is thought to be a key component of threat sensitivity. Despite this theorized relationship, there are inconsistencies within the literature on threat sensitivity and frontal asymmetry. Some work has found that those with greater threat sensitivity— or related constructs such as shyness and behavioral inhibition (characterized by avoidant coping styles and attentional bias to threat; Barker et al., 2019; Perez-Edgar and Fox, 2005)— have greater right frontal asymmetry (Poole et al., 2018; Sutton and Davidson, 1997; Wacker et al., 2009). Other studies, however, have found no relationship (Amodio et al., 2008; Coan and Allen, 2003; Harmon-Jones and Allen, 1997; Hewig et al., 2006).

It could be, however, that *stable* threat sensitivity (i.e., consistently high ST over time) is associated with right frontal asymmetry. Indeed, Degnan and Fox (2007) suggest that individuals who have greater right frontal asymmetry may have a lower threshold for dealing with threatening situations, and thus may be more likely to consistently report a high ST. Although no research has directly tested whether consistently high threat sensitivity is associated with right frontal asymmetry, infants and young children who are consistently classified as behaviorally inhibited or shy have greater right frontal asymmetry than those who are less consistently classified (Fox et al., 2001; Henderson et al., 2001; McManis et al., 2002; Poole et al., 2019). Less is known about stability of threat sensitivity and alpha asymmetry, especially among children and adolescents.

1.3. *Threat sensitivity among children and adolescents*

Childhood and adolescence are important age groups to investigate because adolescence is proposed to be a time of heightened sensitivity to emotionally salient events (e.g., threatening events) compared to children (Casey, 2015; Somerville et al., 2010; Steinberg, 2008). For example, Casey argues in an Imbalance Model that there is asynchrony in the maturation of neural circuits within and between different brain systems, with circuitry within the subcortical limbic-striatal brain system (associated with socioemotional processing) maturing early in adolescence (likely due to puberty), but interconnections to the prefrontal executive system (associated with self-control and potential suppression of socioemotional impulses) maturing later in adolescence. This asynchrony in maturity is thought to lead to heightened activation of the limbic-striatal region during early to mid-adolescence, when neural connections to the prefrontal cortex that might dampen the activation (if appropriate) are not fully mature. As a result, adolescents are thought to be more likely to experience heightened aversive reactions to emotionally provoking negative/threatening events in comparison to children.

In line with these theories, studies have found that subcortical regions (e.g., the amygdala) increase in volume across puberty (Goddings et al., 2014) and mature earlier than higher-order cortices (e.g., prefrontal cortex; Galvan et al., 2006; Gogtay et al., 2004; Mills et al., 2014). Greater pubertal development also has been found to be associated with heightened emotional processing (Dahl and Gunnar, 2009; Goddings et al., 2012, 2019; Schmitz et al., 2014). Indeed, adolescents, compared to children, have been found to have greater sensitivity to threat (Heffer and Willoughby, 2020; O'Brien and Bierman, 1988; Vervoort et al., 2010; Westenberg et al., 2004). Van den Bos et al. (2014) also found that threat sensitivity was more strongly associated with pubertal development than age. Thus, studies find that adolescents may be more sensitive to threats than children. To the best of our knowledge, the question of whether adolescents are more likely than children to report high-stable ST has not been addressed in the literature. Further, whether or not high-stable ST would be associated with right frontal asymmetry remains unknown.

1.4. *The current study*

The present longitudinal study sought to investigate whether consistently high ST is associated with greater neural avoidance motivations (i.e., great right frontal asymmetry) among children and adolescents. First, we used latent class growth curve analysis to investigate whether there are distinct subgroups of children and adolescents based on their self-reported ST across three years. Although this analysis is exploratory, we expected to find a high-stable ST group. We also examined predictors of group membership (e.g., characteristics that predict being in the high-stable ST group). Given that adolescence is thought to be a time of sensitivity to emotionally threatening events, we examined whether older age and more advanced pubertal development would be linked to a greater likelihood of being in the high-stable ST group. We expect based on Casey's Imbalance Model that adolescents would be more likely to report stable high levels of ST than children. Critically, we also examined whether the groups found in the latent class growth curve analysis would differ on right frontal asymmetry scores. We hypothesized that a group characterized by high-stable ST would have greater right frontal asymmetry compared to groups with lower or less stable ST.

2. Method

2.1. *Participants*

Participants (N = 361, age range = 8–14 at year 1, 47.5 % female) were drawn from several elementary and high schools in southern Ontario, Canada, and were surveyed annually across three years. Students were part of a larger study examining the relationship between wellbeing and youth health-risk behaviors. Parents were asked to identify if their child had any illnesses or disabilities (either physical or mental). Two participants were excluded because of a diagnosis of autism, one participant was excluded because they are prone to seizures, and one participant was excluded because of a diagnosis of cerebral palsy. Parent report indicated that 83.7 % of the children and adolescents were White, 1.9 % were Black, 0.8 % were Asian, 1.4 % were Hispanic, 0.6 Indigenous, and 5.5 % were Mixed (a further 0.6 % of parents indicated that they preferred not to answer the question). On average, parental education was "completed a college/apprenticeship and/or technical diploma".

2.2. Procedure

Students were invited to participate in the study through visits to schools. Surveys were completed in classrooms during school hours and all participants received gifts (e.g., backpacks) as compensation. All students who completed the survey in the first year were invited to participate again in the second year. Participants also completed a Mobile Lab component in which their resting EEG was recorded. Given the size of the sample, data collection for the Mobile Lab began in year 2 of the study and finished in year 3. Resting EEG was collected for a total of 4 min (2 min with eyes open and 2 min with eyes closed) while they were seated comfortably. There were 18 participants who had equipment issues during the task (e.g., the event markers did not show up) and two participants did not complete the task. There also were 16 participants who were not included because their EEG data was not usable (e.g., contained a larger number of muscle/movement artifacts). Thus, the final sample included 322 participants. The University Ethics Board approved this study and participants provided informed assent and their parents provided informed consent.

2.3. Missing data analysis

Missing data occurred within each assessment because some participants did not complete the questionnaire (average missing data = 2.433 %), and because some participants were absent during the time of the survey. The percentage of participants absent for the survey at each time point was 6.4 % at Year 1, 4.4 % at Year 2, and 22.7 % at Year 3, respectively. Missing data was primarily due to absenteeism but also occasionally due to time conflicts, students declining to participate in one part of the survey, RA mistakes (e.g., not inviting a child to complete the survey), or students moving to another school district with no contact information. Participants who were absent at one or two of the time points were not significantly different from participants who were there at all three time points on any of the study measures ($p >$ .05). Missing data were imputed using the expectation-maximization algorithm (EM). EM retains cases that are missing survey waves and thus avoids the biased parameter estimates that can occur with pairwise or listwise deletion (Schafer and Graham, 2002).

2.4. Measures

2.4.1. Demographics

Pubertal status, age, sex, and parental education (one item per parent [averaged together] using a scale of 1= *did not finish high school* to 6 = *professional degree*) were collected at all three years. Pubertal status was assessed using the Puberty Development Scale (PDS; Petersen, Crockett, Richards, & Boxer, 1988). The PDS is a self-report measure that assesses body hair, facial hair, and voice development in boys, and body hair, menarche, and breast development in girls. All items were rated on a 4-point scale from 1 (*not yet started changing*) to 4 (*change seems complete*). The PDS scale exhibits good reliability and validity (Carskadon & Acebo, 1993; Petersen et al., 1988).

2.4.2. Sensitivity to threat

At Years 1–3, participants reported the extent to which they agreed with three items specifically examining ST from the Behavioural Inhibition Scale (Carver & White, 1994; “Criticism hurts me quite a bit”, “I feel worried when I think I have done poorly at something”, “I feel pretty worried or upset when I think or know somebody is angry at me”) on a scale ranging from 1 (*Strongly Disagree*) to 4 (*Strongly Agree*). Higher scores indicate higher levels of threat sensitivity. Cronbach’s alpha was 0.77, 0.80, 0.78 at years 1–3, respectively. Of note, we ran an exploratory factor analysis with our items and found that they formed one factor (all factor loadings >.82). We also ran a repeated measures ANOVA to investigate whether the sensitivity to threat increased over time. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that mean sensitivity to threat was significantly different across time points, F(1.9, 684) = 4.942, $p = 0.08$. Post hoc tests using the Bonferroni correction revealed that sensitivity to threat increased between Time 1 and Time 3 ($M_{\text{diff}} = .124$, $SE = .041$, $p = .008$; see Table 2 for means at each time point). This finding is consistent with the idea that sensitivity to threat may increase across adolescence.

2.5. Electrophysiological recording

Electroencephalography (EEG) was recorded continuously from a BioSemi ActiveTwo system using a 96-channel montage and 7 face sensors. The data were digitized at a sampling rate of 512 Hz. Pre-processing was conducted to identify (1) channels/components that were unreliable within a given time-period, (2) time-periods that were unreliable, (3) and channels/components that were unreliable throughout the recording.

2.6. Pre-processing (channels)

Pre-processing was automated (using MATLAB 2012b scripts) to be carried out using EEGLAB (Delorme & Makeig, 2004) version 13.6.5b and was then executed using Octave on Compute Canada’s high performance computer cluster (Cedar; see Desjardins & Segalowitz, 2013; van Noordt, Desjardins, & Segalowitz, 2015; van Noordt, Desjardins, Gogo, Tekok-Kilic, & Segalowitz, 2017 for more details).The data were first separated into 1 s non-overlapping time windows. For each time window, the voltage variance across each channel was calculated (a 20 % trimmed mean was used). Channels were flagged as unreliable if they had a z-score six times greater than the voltage variance across all channels. Time-periods (i.e., the 1 s time windows) were considered unreliable if more than 10 % of the channels were identified as having extreme voltage variances. Finally, any channels that were flagged in more than 20 % of the time-periods were considered unreliable throughout the recording.

The data were re-referenced to an interpolated average of 19 sites, excluding flagged channels. The data were filtered with a 1 Hz high pass and 30 Hz low pass filter given that cortical activity would not be expected to exceed 30 Hz. After this step, the data were again checked for the same issues reported above: (1) channels that are unreliable within a given time-period, (2) time-periods that are unreliable, (3) and channels that are unreliable throughout the recording. Specifically, any channels that were unlike its neighbouring channels (e.g., had a low correlation with channels around it), were flagged. A channel was flagged as unreliable if it had a z-score that was 2.326 times greater than the mean of the 20 % trimmed distribution of correlation coefficients. Time-periods were considered unreliable if more than 10 % of the channels within the window were flagged as unreliable. Any individual channels that were flagged in more than 10 % of time-periods were considered unreliable across the entire recording. Bridged channels (i.e., channels that are highly correlated with invariable signal) were identified after dividing the average maximum correlation by the standard deviation of the distribution of correlation coefficients. Channels that had a positive z-score that was eight times greater than the 40 % trimmed distribution of coefficients were flagged as bridged channels.

2.7. Pre-processing (components)

After pre-processing the channel data, all data that had not been flagged as unreliable was concatenated back into continuous data. These data were then submitted to an initial Adaptive Mixture of Independent Component Analysis (AMICA) to identify different components of the EEG data (e.g., heart rate components, eye blink components, cortical components etc.). This process helps to separate brain activity (neural components) from non-neural activity (e.g., muscle movement).

During this procedure, the data were windowed into 1 s time epochs. Unreliable components were detected by comparing each individual component to the variance among all components. Components were flagged if they had a z-score that was 2.326 times greater than the trimmed mean. Time-periods that had more than 10 % of its components flagged were considered unreliable. The data were then concatenated into the continuous time course and submitted to three simultaneous AMICA decompositions to assess whether components were replicable (i.e., is muscle movement consistently being classified as muscle movement when the process is repeated multiple times). The procedure above for identifying unreliable components (within 1 s epochs) was completed again using the continuous time series data. Next, a dipole (which identifies the position and orientation for the distribution of positive and negative voltages) was fit using the dipfit plugin in Matlab (Oostenveld, Fries, Maris, & Schoffelen, 2011). Components with a dipole fit residual variance greater than 15 % were flagged. Finally, components were classified using the ICMARC plugin. This process assesses each component against a crowd-sourced database to identify activation consistent with five different categories: eye blinks, neural, heart, lateral eye movements, muscle contamination, and mixed signal.

After pre-processing, a manual quality control review was completed to ensure that the decisions made during pre-processing were appropriate. This procedure was completed by one trained research assistant who assessed the accuracy of the independent component classifications. For example, the research assistant would identify whether cortical components were correctly distinguished from non-cortical components (e.g., muscle, eye blinks, etc.) based on topographical projection, continuous activation, dipole fit and power spectrum profile. Thus, the quality control review involved using the independent components to help with artifact correction.

2.8. *EEG post-processing*

Resting EEG was recorded for a total of 4 min (2 min with eyes open [EO], 2 min with eyes closed [EC]). Consistent with previous studies, frontal alpha (8−13 Hz) was measured at F3 (left scalp location) and F4 (right scalp location; Allen et al., 2004; Davidson, 2000; Poole et al., 2019; Schmidt, 1999). The average of EO and EC conditions were taken. The data were then log(ln) transformed to correct for skewed distributions. To get a measure of alpha asymmetry, power from the left site was subtracted from power from the right site (Ln F4-Ln F3). Positive scores (greater right than left *alpha* activation) represent greater relative left cortical activation while negative scores (greater left than right *alpha* activation) represent greater relative right cortical activation. The range of alpha asymmetry scores for this sample was −2.87 to 2.59 ($M = -.622$, $SD = .717$).

2.9. *Plan of analysis*

A latent class growth curve analysis was conducted using Mplus 7 (Muthén & Muthén, 2012). We used *MplusAutomation* (Hallquist and Wiley, 2018), a package in R (R Core Team, 2019), to automate the latent class growth curve analysis and extract the model parameters from Mplus. ST was measured at all three time points and used as latent class indicators. In order to determine the number of groups that were best represented by the data, four criteria were considered: 1) interpretability of the classes, 2) Bayesian information criterion (BIC), such that smaller values of BIC indicate a better fit model, 3) significance of the Lo-Mendell-Rubin Likelihood Ratio Test (LMR-LRT) significance value— once non-significance is reached, the number of classes prior to non-significance is defined as the appropriate number, and 4) average latent class conditional probabilities are close to 1.00 (Nylund et al., 2007).

After establishing the existence of latent classes, a multinomial logistic regression was run to establish whether demographic variables at year 1 (sex, age, parental education and pubertal status) predicted group membership (see Fig. 1 for correlations between demographic variables).

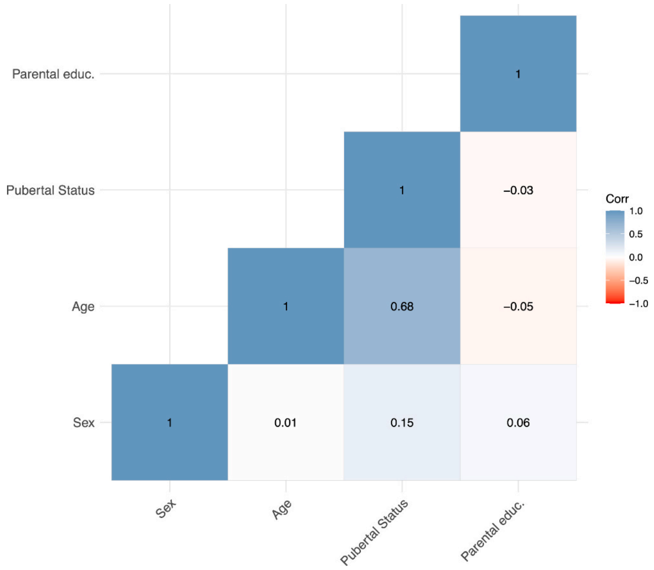

Fig. 1. Bivariate correlations for the demographic variables. The plot was made using ggcorrplot in R (Lishinski, 2018). Of note, sex was coded as 0 = male, 1 = female.

Class differences in alpha asymmetry were examined using an ANCOVA, with alpha asymmetry as the dependent variable and class as the independent variable. Sex, parental education, age and pubertal status were included in the analysis as covariates. Of note, the EEG data collection occurred in year 2 and year 3 of the study; therefore, age and pubertal status may be different depending on what year the EEG data was collected. To account for this, we created variables that used year 2 demographics for participants who completed the lab in year 2, and year 3 demographics for participants who completed the lab in year 3. Thus, we were able to control for age and pubertal status in the year that participants completed the mobile lab.

3. Results

3.1. *Latent class growth curve analysis*

The latent class growth analysis was conducted for 1–4 classes. The three-class solution was chosen as the best classification of the data (see Table 1). This classification had the lowest BIC, and a LMR-LRT significance value that was significant at 3 classes but not at 4 classes, indicating that three classes was a better fit to the data. This solution also was interpretable and had conditional probabilities close to 1.00. The three groups were characterized as follows: low-stable ST (LowStb ST; 14.0 % of the sample), moderate-increasing ST (ModInc ST; 54.3 % of the sample) and high-stable ST (HighStb ST; 31.7 % of the sample). See Fig. 2 for an illustration of the groups. The means for threat sensitivity across all three time points for each group, and the slopes, are presented in Table 2. ANOVAs revealed that the three groups were significantly different from each other on ST at all three years ($ps < .001$).

Table 1
Latent Class Analysis fit indices.

Number of Classes	BIC	Entropy	Conditional Probabilities	LMR Significance	BLRT Significance
2 Classes	2221.13	0.78	0.91−0.95	0.0006	<0.00
3 Classes	2180.03	0.70	0.85−0.93	0.0008	<0.00
4 Classes	2181.65	0.71	0.76−0.90	0.1097	<0.00

Note. BIC = Bayesian information criterion. LMR = Lo-Mendell-Rubin, BLRT = Bootstrapped Likelihood Ratio Test.

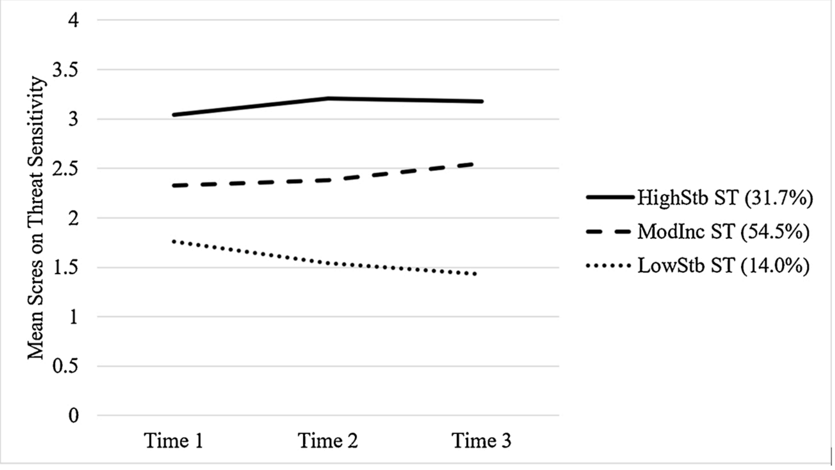

Fig. 2. Results of the latent class growth curve analysis. ST = Sensitivity to threat.

Table 2
Group Means on Sensitivity to Threat and Their Slopes.

	Low-stable ST	Mod-increasing ST	High-stable ST	Overall ST
Mean1 (*SD*)	1.76(0.73)	2.33(0.64)	3.04(0.55)	2.47 (0.76)
Mean2 (*SD*)	1.54(0.51)	2.38(0.57)	3.21(0.44)	2.52 (0.75)
Mean3 (*SD*)	1.43(0.40)	2.55(0.32)	3.18(0.36)	2.59 (0.65)
Slope (*SD*)	−0.15(0.09)	0.13(0.03)***	0.05(0.04)	

Note. Mod = moderate, ST = sensitivity to threat. Means 1, 2, and 3 represent the means.
at Years 1, 2 and 3 of the study, respectively. SD = Standard deviation. ***p<.001.

3.2. *Predictors of group membership*

Multinomial logistic regression was used to predict whether sex, parental education, age and pubertal status were associated with group membership. Means and standard deviations for the demographic variables across the different groups are presented in Table 3. Group status (LowStb ST, ModInc ST, HighStb ST) was entered as the dependent variable and sex, parental education, age and pubertal status were entered as the independent variables. The overall model was significant $\chi2(8) = 48.38$, $p < .001$. Sex ($p < .001$), parental education ($p = .009$) and pubertal status (p = .002) significantly differentiated among the classes. Females had greater odds of being in the HighStb ST (OR = 5.094, $p < .001$) and ModInc ST (OR = 3.631, $p = .001$) groups than in the LowStb ST group. Further, individuals with higher parental education had greater odds of being in the HighStb ST group compared to the ModInc ST group (OR = 1.554, $p = .003$) and compared to LowStb ST group (OR = 1.531, $p = .046$). Participants with greater pubertal development had higher odds of being in the HighStb ST group compared to the ModInc ST group (OR = 2.217, p = .011) and compared to the LowStb ST group (OR = 4.869, $p = .004$). There were no other significant differences (of note, we also re-ran the model with only age, sex and parental education as predictors. In this model, age was not a significant predictor of class, $p = .066$).

3.3. *Differences among classes on alpha asymmetry*

An ANCOVA was run with alpha asymmetry scores as the dependent variable and class (LowStb ST, ModInc ST, HighStb ST) as the between-subjects factor. Sex, parental education, age and pubertal status were included as covariates. There was a significant main effect of class F(2, 299) = 3.383, $p = .035$. Post hoc analyses revealed that the HighStb ST group had more negative alpha asymmetry scores (i.e., right frontal asymmetry; $M = -.777$, $SD = .686$) than the ModInc ST group ($M = -.551$, $SD = .746$) and the LowStb ST group ($M = -.547$, $SD = .623$), *ps* $< .05$. There were no differences found between the ModInc ST group and the LowStb ST group ($p = .976$). The covariates were not associated with alpha asymmetry ($p > .05$; see Table 4).

4. Discussion

Avoidance motivation is thought to be an important component of threat sensitivity. However, research on right frontal asymmetry, a neural index of avoidance tendencies, and threat sensitivity is mixed. It may be that *stable* threat sensitivity (i.e., consistently high ST over time) is associated with right frontal asymmetry. Indeed, Degnan and Fox (2007) suggest that individuals who have greater right frontal asymmetry may have a lower threshold for dealing with threatening situations, and thus may be more likely to consistently report a high ST. The current study examined whether developmental trajectories of threat sensitivity (e.g., consistently reporting high ST) are associated with right frontal asymmetry in a sample of children and adolescents. This age group is particularly important to examine given that adolescence is thought to be a time of increased sensitivity to emotionally salient events (Casey, 2015; Somerville et al., 2010; Steinberg, 2008)—perhaps heightening their ST compared to children. To address these questions, we first conducted a latent class growth curve analysis to investigate

Table 3
Means and standard deviations of the demographic variables as a function of group.

Demographic Variables	Low-stable ST	Mod-increasing ST	High-stable ST
Sex	20.0 % Female	47.7 % Female	59.6 % Female
Parental Education	4.04(0.94)	4.05(0.87)	4.31(0.84)
Age	9.76(1.41)	9.67(1.47)	10.00(1.40)
Pubertal Status	1.25(0.40)	1.36(0.50)	1.57(0.65)

Note. Mod = moderate, ST = sensitivity to threat.

Table 4
Results of the ANCOVA for Group Differences on Alpha Asymmetry.

	df	F	*p*	$\eta^2 p$
Sex	1	1.486	.224	.005
Parental Education	1	.038	.845	.000
Age	1	2.219	.137	.007
Pubertal Status	1	1.672	.197	.006
Group membership	2	3.383	.035*	.022

Note: *p < .05.

different trajectories of ST. Next, we examined predictors of group membership, specifically to identify whether adolescents (as measured by age and pubertal status) were more likely to be part of the high-stableST group. Critically, once we established the developmental trajectories, we investigated whether these trajectories were associated with right frontal asymmetry.

Results from the latent class growth curve analysis identified three distinct trajectories: as predicted, a HighStb ST group was found, representing a third of the sample. We also found a smaller LowStb ST group (14.0 % of the sample), and a ModInc ST group, representing 54.3 % of the sample. The most common trajectory among this age group, therefore, was moderate yet increasing ST across the three years. This finding suggests that it may be normative for children and adolescents to report slightly higher levels of ST as they get older. Further, 32 % of our sample were classified as HighStb ST, highlighting that a relatively large proportion of children and adolescents are reporting consistently high sensitivity to threat.

Pubertal status, but not age, predicted greater odds of being in the HighStb ST group than in the other two groups. Indeed, neurodevelopmental imbalance models highlight that changes in neural circuitries in early adolescence, hypothesized to lead to increased sensitivity to emotionally salient events, may be a result of pubertal development. Our results are consistent with this model: more advanced pubertal development, rather than age, was a better indicator of being in the HighStb ST. A strength of this study is that we used both age and pubertal status as predictors of group membership. Indeed, if we had only used age in our model, we would have missed an important finding relating to puberty (one that is in line with the Casey’s Imbalance Model, 2015).

We also found that females had greater odds of being in the HighStb ST and ModInc ST groups compared to LowStb ST group. This is perhaps not surprising given that females tend to reach puberty earlier, and thus, may have increased ST, resulting in greater odds of being in the higher ST groups at Time 1 in comparison to males. This finding is consistent with some studies showing that females report greater ST than males (Santesso et al., 2011; Tull et al., 2010). We also found that participants with *greater* parental education had higher odds of being in the HighStb ST group compared to the ModInc ST group and the LowStb ST group. Although this finding was not among our main hypotheses, we speculate that perhaps children and adolescents who have parents with higher levels of education may feel more pressure to succeed and thus may report feeling worse about threatening events (e.g., receiving criticism).

A key interest in this study was whether frontal asymmetry was associated with the trajectories of ST. We found that the HighStb ST group had greater right frontal asymmetry scores compared to the other groups. These results are consistent with previous research suggesting that *stable* and higher behavioral inhibition (a related construct) is associated with right frontal asymmetry in a small group of infants and young children (e.g., Chronis-Tuscano et al., 2009; Fox et al., 2001). Therefore, when individuals report or exhibit stable high ST, they show neural activation consistent with greater avoidance motivation. A strength of our study was the combining of EEG methods with self-report. This combination provides a more comprehensive understanding of ST across development. Our findings indicate that not only do those with more advanced pubertal development have greater odds of being in the HighStb ST group, there also are neural differences associated with this pattern of reporting.

Despite the strengths of our study, there are several limitations. First, EEG was collected across two years of the study; thus, not all student’s EEG data was collected in the same year. This is not surprising given the size of our sample of children and adolescents. Although a large sample was critical to identify distinct groups of children and adolescents on threat sensitivity, the design of our study does not allow for us to investigate whether alpha asymmetry is a predictor of stable threat sensitivity. To test this question, an optimal design would be to collect EEG and sensitivity to threat data at each time point. In doing so, future research would be able to examine the direction of effects between threat sensitivity and alpha asymmetry over time (i.e., does greater right frontal asymmetry predict more stable threat sensitivity and/or does more stable threat sensitivity predict greater right frontal asymmetry over time).

Second, our sensitivity to threat measure was a composite of three items from the BIS measure as opposed to the full BIS measure. As the data were part of a larger study assessing a wide range of constructs, it was not feasible to include every item from the BIS scale. Of note, however, the alpha for the measure used in this study ranged from .77 to .80 across the three years, demonstrating good reliability (Cronbach, 1951). Third, our measure of threat sensitivity was designed in accordance with the original Reinforcement Sensitivity Theory; however, revisions to the theory suggest that anxiety may result from *conflict* between both avoidance and approach motivation (Gray and McNaughton, 2000). Future research should investigate whether frontal asymmetry is associated with a revised measure of the Reinforcement Sensitivity Theory, one that addresses this approach/avoidance conflict. Fourth, our study had a large percent (22.7 %) of missing data at year 3 due primarily to absenteeism. Given that the questionnaires used for this study were administered during class time, we had no control over whether students would be absent or unavailable during that time period. Finally, our overall sample had a mean alpha asymmetry score of −.622; thus, our overall sample tended to have greater right than left frontal asymmetry. Although this was not expected, some studies also have found greater right than left frontal asymmetry among children and adolescents (e.g., Winegust et al., 2014).

Overall, this large longitudinal study has important developmental implications. In support of current neurodevelopmental models, more advanced pubertal development may be an important measure for identifying those who will report stable high ST. We did not find this same pattern of results with age; thus, our results suggest that puberty is a better marker of distinct trajectories of ST than age. Additionally, the HighStb ST group had greater right frontal asymmetry than the other groups. Thus, the current study highlights that sensitivity to threat seems to have important neurological underpinnings associated with both puberty and alpha activation in the brain.

Although advanced pubertal development predicted membership in the HighStb ST group, it is important to note that puberty would not be expected to increase ST among all youth. Instead, our results suggest that advanced pubertal development increases the odds of being specifically in the HighStb ST group. However, this group represented only 31 % of the sample; thus, there are clear individual differences in ST across development. Future research should extend these findings to investigate how these trajectories of ST may change beyond adolescence (i.e., is there a percentage of the HighStb ST group that *remains* consistently sensitive to threat into adulthood?). Given that stable ST has been found to be associated with anxiety, identifying groups of individuals with (and neural predictors of) high/stable ST is of critical importance.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgement

The second author acknowledges funding for this study received from Canadian Institutes of Health Research.

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