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Electroencephalogram Coherence in Children With and Without Autism Spectrum Disorders: Decreased Interhemispheric Connectivity in Autism

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Abstract

Electroencephalogram coherence was measured in children with autism spectrum disorders (ASD) and control children at baseline and while watching videos of a familiar and unfamiliar person reading a story. Coherence was measured between the left and right hemispheres of the frontal, parietal, and temporal-parietal lobes (interhemispheric) and between the frontal and parietal lobes in each hemisphere (intrahemispheric). A data-reduction technique was employed to identify the frequency (alpha) that yielded significant differences in video conditions. Children with ASD displayed reduced coherence at the alpha frequency between the left and right temporal-parietal lobes in all conditions and reduced coherence at the alpha frequency between left and right frontal lobes during baseline. No group differences in intrahemispheric coherence at the alpha frequency emerged at the chosen statistical threshold. Results suggest decreased interhemispheric connectivity in frontal and temporal-parietal regions in children with ASD compared to controls.

Keywords

electroencephalography; EEG coherence; school age < pediatrics; social brain

Autism spectrum disorders (ASD) are recognized as brain-based disorders [Dawson, **2008**] with key social deficits [Asperger, **1944**]. Yet, the underlying neurology of the social impairments in ASD is still not well understood. Recent theoretical and empirical work [Barttfeld et al., **2011**; Just, Cherkassky, Keller, Kana, & Minshew, **2007**; Just, Keller, Malave, Kana, & Varma, **2012**; Rippon, Brock, Brown, & Boucher, **2007**] indicates that a cardinal issue in ASD may be deficits in long-range neural connectivity. However, most studies in this area have examined “long-range connectivity” exclusively as intrahemispheric tracts connecting the frontal cortex with more posterior areas [see Schipul, Keller, & Just, **2011**, for review; Murias, Webb, Greenson, & Dawson, **2007**]. Few studies have applied the idea of decreased “long-range connectivity” to circuits connecting the left and right hemispheres of the brain at anterior or posterior regions [but see Coben, Clarke, Hudspeth, & Barry, **2008**]. The current study used electroencephalogram (EEG) coherence to investigate functional neural connectivity within and between hemispheres in children with ASD and typically developing controls who viewed videos of familiar and unfamiliar people engaging in a social interaction.

Neural Regions Associated with Social Behavior in ASD

Regions of the frontal and parietal-temporal lobes have been implicated in the processing of social behaviors that are commonly impaired in ASD [Amaral, Schumann, & Nordahl, **2008**; Saxe, **2006**]. More specifically, a complex ventromedial “social brain” circuit has been posited to include the orbito-frontal cortex, temporal cortical areas, and ventral subcortical areas, such as the amygdala [Adolphs, **2001**; Brothers, **1990**]. The frontal lobe is associated with higher order functions including planning of future activities, reasoning about the mental states of others, and executing motor behaviors [Adolphs, **2001**; Courchesne & Pierce, **2005b**]. Anatomical deviations [Amaral et al., **2008**; Courchesne & Pierce, **2005b**] and differences in brain activity [Dawson, Klinger, Panagiotides, Lewy, & Castelloe, **1995**] have been found in the frontal lobes in ASD, including during the processing of familiar and unfamiliar faces [Pierce, Haist, Sedaghat, & Courchesne, **2004**]. The parietal-temporal lobe is also implicated in many behavioral interactions with the world, including the processing of facial details and emotions [Mundy & Neal, **2001**]. The parietal-temporal lobe shows unique structural deviations [Brieber et al., **2007**] and abnormal activity in ASD. For example, the fusiform gyrus exhibits dramatically reduced activity when people with ASD process faces of strangers [Pierce, Müller, Ambrose, Allen, & Courchesne, **2001**], whereas familiarity with social partners may result in a more neuro-typical response in the temporal area of the “social brain” [Pierce et al., **2004**].

Theories of Neural Connectivity in ASD

The complex nature of social interactions requires integration of a multitude of cognitive and emotional signals. One theory posits that integrative neural circuitry in ASD is underconnected, causing deficits in the integration of neural and cognitive information [Just, Cherkassky, Keller, & Minshew, **2004**; Rippon et al., **2007**]. This idea is supported by imaging and post-mortem studies of ASD that show reduced long-distance connections between frontal cortex and other cortical regions compared to typically developing individuals [Courchesne & Pierce, **2005b**], although local (short-range) connections within the frontal cortex may also be increased and disorganized compared to controls. It has been suggested that reduced “long-range” connectivity may particularly impact cortico-cortico connectivity targeting frontal areas thereby affecting higher order processing and executive functions [Just et al., **2007**].

Estimates of functional connectivity have been obtained using magnetic resonance imaging (MRI) and EEG to measure the extent to which different areas of the brain reciprocally interact. EEG coherence estimates the extent to which signals recorded under one EEG electrode can be predicted as a linear function of signals recorded under another EEG electrode. EEG coherence can therefore be regarded as an estimate of functional connectivity that quantifies the amount of synchronization between two electrode channels [Nunez & Srinivasan, **2006**]. Coherence values range between zero and one. Values close to one indicate linear correlation in the electrical signals of two electrodes, whereas values close to zero indicate that the signals recorded at the two electrodes are unrelated in a linear sense. Depending on which EEG electrode pairs are selected for analysis, EEG coherence can estimate connectivity within each individual hemisphere and/or between the hemispheres. Thus, EEG coherence may be a useful tool in investigating connectivity in ASD in order to better understand the short- and long-range neural connections in ASD.

Interhemispheric Connectivity

Cortico-cortical interhemispheric connections are vital for complex information processing. Understanding how they are impacted in children with ASD is essential for understanding socio-behavioral deficits [Minshew, Goldstein, & Siegel, **1997**]. However, few studies have specifically addressed interhemispheric connectivity in ASD. One exception is a study by Coben and colleagues [**2008**], who reported decreased EEG coherence in the alpha frequency band (7.81 Hz to 12.70 Hz) between the left and right temporal lobes in children with ASD relative to typically developing children. Decreased EEG coherence suggests a decrease in functional connectivity across the hemispheres in an area known to contribute to social processing.

The corpus callosum (CC) consists of about 200 million axons connecting the left and right hemispheres and is the largest white matter structure in the brain [Giedd, **2008**]. The CC has become an area of interest in ASD because of its involvement in interhemispheric transfer of sensory information relevant to multiple cognitive processes [e.g., Mathias et al., **2004**; Pollmann, Maertens, & von Cramon, **2004**; Schulte, Sullivan, Müller-Oehring, Adalsteinsson, & Pfefferbaum, **2005**] and because of findings that the CC may not develop typically in persons with ASD. Specifically, the CC is smaller in ASD compared to control groups, regardless of age [Alexander et al., **2007**; Freitag et al., **2009**; Vidal et al., **2006**]. The midsagittal region of the CC in young children with autism also appears to have higher mean magnetization transfer ratio (MTR) than in typically developing controls, suggesting abnormal myelination in this region of the CC in early development [Gozzi et al., **2012**]. Abnormal myelination in the CC in ASD could potentially impact long-range connectivity in ASD, resulting in disrupted or reduced interhemispheric connectivity in ASD.

The rare neurological condition, agenesis of the corpus callosum (AgCC), provides important insights in understanding this structure's significance. In AgCC, the CC is incomplete or absent at birth. Because people with AgCC exhibit social communication and social interaction deficits, it is thought that the CC contributes to

connectivity between brain areas supporting social function. Additionally, children and young adults with comorbid tuberous sclerosis complex and ASD display more significantly altered white matter microstructural organization in the CC compared to typically developing children than children with only tuberous sclerosis complex [Peters et al., **2012**]. Because the range of social communication and social interaction deficits in people with AgCC overlap with the diagnostic criteria for ASD [Paul et al., **2007**], understanding connectivity between the two hemispheres is important for understanding the underlying neurobiology of ASD.

Intrahemispheric Connectivity

Reduced intrahemispheric EEG coherence in the alpha band has been found between frontal and parietal lobes in persons with ASD as compared to neurotypical persons during an eyes-closed resting state [Murias et al., **2007**]. ASD-related underconnectivity during resting state has also been obtained by analyzing EEG coherence within the delta [0 Hz to 3.9 Hz] and theta [3.9 Hz to 7.8 Hz] frequency bands using intrahemispheric electrode pairs spanning the frontal and temporal lobes [Coben et al., **2008**]. This latter finding was corroborated by Barttfeld et al. [**2011**], who found reduced EEG coherence in the delta band between frontal and occipital regions in ASD (although the frontal regions investigated included medial frontal areas, making it difficult to discern if these long-distance connections were exclusively intrahemispheric or if they were both intrahemispheric and interhemispheric).

The Present Study

The present study extended the analysis of an existing dataset originally collected during experiments described in Vaughan Van Hecke et al.'s [**2009**] paper. Here, EEG coherence was utilized to estimate inter- and intra-hemispheric functional connectivity between the frontal, parietal, and temporal-parietal lobes in children with and without ASD. Estimations were performed during a baseline condition and two conditions utilizing dynamic visual stimuli of familiar and unfamiliar people. The task conditions were intended to simulate daily social interactions and to allow better understanding of neural processes germane to social deficits. This research sought to determine whether visual stimuli that simulate social interactions elicit different patterns of activity and connectivity in children with ASD vs. typically developing children. It was hypothesized that relative to typically developing children, those with ASD would demonstrate decreased EEG coherence (i.e., long-range connectivity) between the hemispheres as well as between the lobes within each hemisphere.

Methods

Participants

Nineteen children with high-functioning ASD (1 female; aged 9.95 ± 1.61) and 13 typically developing children (TYP: 4 females; aged 10 ± 1.63) participated. All procedures were approved by the Internal Review Boards of the authors' universities and followed the guidelines of the Declaration of Helsinki. Participants were included if their intelligence quotient (IQ) on the Kaufman Brief Intelligence Test [Kaufman & Kaufman, **2005**] was above 75 and if they sat quietly while viewing video stimuli. Participants did not differ between groups on age ($t(30) = -0.900, P = 0.929$) or IQ ($t(30) = -0.252, P = 0.802$). ASD diagnosis was verified using the Autism Diagnostic Observation Schedule [ADOS: Lord, Rutter, Dilavore, & Risi, **1999**]. TYP children were included if they had no history of ASD, no history of other developmental disorders or psychopathology, and scored below clinical cutoffs on all subscales of the Child Behavior Checklist [Achenbach & Rescorla, **2001**]. Descriptive characteristics of participants are presented in Table 1. More details on subject characteristics and recruitment can be found in Vaughan Van Hecke et al.'s (**2009**) paper.

Table 1. Demographic Information

	ASD group	TYP group
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Gender ratio (Male/Female)	18/1	9/4
Age (y)	9.95 ± 1.61	10 ± 1.63
Race/Ethnicity ^a		
Caucasian	14	4
African-American	4	8
K-BIT Total Score	102.42 ± 17.92	104.15 ± 20.69

K-BIT, Kaufman Brief Intelligence Test.

Data are presented as mean ± SD.

^a denotes statistically significant difference between the group means at $P < 0.05$.

Procedures

Participants sat in a comfortable reclining chair and viewed a video screen (~1 m away), while continuous EEG data was collected. After 3 minutes of baseline data collection of watching a blank video screen, participants then watched two 5-minute videos of a person reading a story. The videos differed in the person who narrated the story. The person was either a *familiar* person (the participant's caregiver), or an *unfamiliar* person (i.e., another child's caregiver) who had never met the participant. The presentation order of videos was randomly assigned, and the stories read by the familiar and unfamiliar person were different for each participant. Children were not aware their caregiver would be included in the video. In each video, the narrator faced forward and made eye contact toward the camera. Continuous EEG was collected for all three conditions in a single session that lasted approximately 16 minutes.

EEG recordings were measured with a 64-channel electrode cap (Neuroscan, Inc, Charlotte, NC). All impedances were maintained at ≤ 10 kOhm. EEG signals were amplified and digitized at a sampling rate of 1,000 samples/sec (Synamps 2, Neuroscan, Inc, Charlotte, NC). A CZ reference was used during recording. Eye movements were monitored using hanging electrodes placed on the outer canthus of both eyes and above and below the left eye.

Data Analysis

Data were analyzed off-line. EEG, measured in microvolts, was re-referenced post-acquisition to the average of left/right mastoid signals. Eye movement data recorded from electro-oculogram channels were used to manually identify and remove segments of raw EEG data contaminated by muscle activity and eye artifact. EEG data were separated into 1-second epochs with 50% overlap between consecutive epochs. A minimum of 30 artifact-free epochs was required to include a participant's data in subsequent analyses. A *t*-test revealed that the number of accepted epochs did not significantly differ between the groups. Epoch data were extracted via Fast Fourier Transform using a Hamming window to gain estimates of coherence using the Compumedics-Neuroscan Scan 4.3 analysis program (Neuroscan, Inc., Charlotte, NC, USA). Coherence was measured at four frequency bands: delta [0 to 3.91 Hz], theta [3.91 to 7.81 Hz], alpha [7.81 to 12.70 Hz], and beta [12.70 to 29.30 Hz], using the coherence transform in the Neuroscan Edit 4.3 (Charlotte, NC) program. The method of spectral coherence measured does not distinguish between phase coherence vs. amplitude coherence but reflects both [Sauseng & Klimesch, 2008]. Coherence values, C_{xy} , were calculated for each frequency bin, λ , according to the following equation:

$$C_{xy}(\lambda) = \frac{|P_{xy}(\lambda)|^2}{P_{xx}(\lambda)P_{yy}(\lambda)}$$

where $P_{xy}(\lambda)$ is the cross-spectral density between the two signals x and y , whereas $P_{xx}(\lambda)$ and $P_{yy}(\lambda)$ are the corresponding autospectral densities.

The coherence equation is the extension of the Pearson's correlation coefficient to complex number pairs [Hummel & Gerloff, **2005**]. Because coherence data are not normally distributed, a square root transformation was applied in order to approximate Pearson's *r* values, which were then normalized using a Fisher *z*-transform of the approximated Pearson's *r* values [see Enochson and Goodman, 1965, cited in Tucker & Roth, **1984**].

Prior studies suggest that the activity and structure of the frontal and parietal-temporal cortices are uniquely affected in ASD and that abnormalities in these regions are associated with common social deficits in ASD [Blakemore, **2008** for review]. Therefore, only those electrode pairs germane to the hypothesis that frontal and parietal-temporal regions are impaired in ASD were included in the analyses to limit family-wise error rates (which would be unacceptably high if all possible electrode pairs were included in the analysis). Thus, coherence values between five relevant pairs of electrodes were used: (a) right frontal/left frontal (F5-F6); (b) right parietal/left parietal (P5-P6); (c) right temporal-parietal/left temporal-parietal (TP7-TP8); (d) left frontal/left parietal (F5-P5); and (e) right frontal/right parietal (F6-P6). Normality was assessed using the Anderson-Darling test, and variance was compared across groups in each of the video, electrode pair, and frequency band combinations using the *F*-test in Minitab software (Minitab Inc., State College, PA). All subsequent statistical tests were performed in IBM SPSS Statistics version 20 software (SPSS, Inc., Chicago, IL).

First, repeated measures analysis of variance (RM-ANOVA) was used to compare coherence with group (ASD or TYP) as a between-subject factor and with the following within-subject factors: video (baseline, familiar, or unfamiliar), electrode pair (F5-F6, P5-P6, TP7-TP8, F5-P5, or F6-P6), and frequency band (delta, theta, alpha, or beta). This analysis strategy identified two significant three-way interactions: between frequency band × electrode pair × group and between frequency band × electrode pair × video. Therefore, four separate RM-ANOVAs were conducted (one for each frequency band, using group as a between-subject factor, and video condition and electrode pair as within-subject factors) to identify the frequency band that yielded the most significant differences in coherence related to the task. Finally, five separate RM-ANOVAs were conducted, one for each electrode pair at the frequency band identified above using group as a between-subject factor and video condition as a within-subject factor. The Huynh-Feldt correction was used to correct for violations of sphericity. Bonferroni correction was used for the final five RM-ANOVAs computed for each electrode pair. Effects were considered statistically significant at the $\alpha = 0.05$ level.

Results

All participants followed task instructions. Analysis of normality revealed that one typically developing participant's coherence data was largely outside the group mean (on average, one standard deviation outside the group mean); therefore, this participant's data was excluded from further analysis. Assumptions of normality and equality of variances were accepted given the results of the Anderson–Darling normality test and the *F*-test.

RM-ANOVA found significant main effects of group ($F(1,22) = 5.2, P = 0.033$), frequency band ($F(2.4, 52.6) = 17.6, P < 0.001, \epsilon = 0.797$) and electrode pair ($F(3.6, 79.3) = 120.0, P < 0.001, \epsilon = 0.901$). In addition, two significant three-way interactions were found: frequency band × electrode pair × group ($F(8.6, 188.1) = 3.1, P = 0.002, \epsilon = 0.712$) and frequency band × electrode pair × video ($F(14.8, 326.4) = 1.734, P = 0.044, \epsilon = 0.618$).

To follow up on the three-way interactions, four RM-ANOVAs were computed, one for each frequency band, with video and electrode pair as within-subjects factors and group as a between-subject factor. These RM-ANOVAs were used to select only those frequency bands that had significant video and/or group effects. A main effect of electrode pair was found for each of the frequency bands tested ($P < 0.001$). In addition, a main effect of group was found for the beta frequency band ($F(1,22) = 10.5, P = 0.004$). An electrode × group interaction was also found in the alpha [$F(3.3, 75.5) = 5.7, P = 0.001, \epsilon = 0.821$], beta [$F(3.1, 67.9) =$

5.0, $P = 0.003$, $\varepsilon = 0.772$], and theta [$F(2.7, 62.0) = 3.8$, $P = 0.018$, $\varepsilon = 0.674$] frequencies. An electrode \times video interaction was seen for the alpha [$F(4.6, 106.5) = 2.9$, $P = 0.021$, $\varepsilon = 0.579$] and theta [$F(4.6, 106.2) = 3.0$, $P = 0.018$, $\varepsilon = 0.577$] frequencies. Lastly, the alpha frequency alone exhibited a main effect of video [$F(1.2, 28.7) = 5.5$, $P = 0.021$, $\varepsilon = 0.623$]. Since the primary interest of this analysis was in frequency bands that distinguish task conditions, only the alpha band was used for subsequent analyses. Please see Table 2 for Z-transformed coherence values and raw coherence values in the alpha frequency.

Table 2. Z-Transformed and Raw Alpha Coherence Data

	Z-Transformed data	[Mean \pm SD]	Raw data ^b	[Median (Interquartile range)]
Electrode location	ASD Alpha Coherence	TYP Alpha Coherence	ASD Alpha Coherence	TYP Alpha Coherence
Right/Left-frontal baseline	0.62 \pm 0.16 ^a	0.75 \pm 0.21 ^a	0.310 (0.092)	0.389 (0.260)
Right/Left-frontal familiar	0.57 \pm 0.14	0.60 \pm 0.15	0.282 (0.131)	0.267 (0.160)
Right/Left-frontal unfamiliar	0.58 \pm 0.14	0.61 \pm 0.17	0.279 (0.170)	0.300 (0.172)
Right/Left-temporal-parietal baseline	0.22 \pm 0.08 ^a	0.35 \pm 0.11 ^a	0.045 (0.030)	0.114 (0.076)
Right/Left-temporal-parietal familiar	0.19 \pm 0.10 ^a	0.34 \pm 0.11 ^a	0.026 (0.042)	0.101 (0.064)
Right/Left-temporal-parietal unfamiliar	0.20 \pm 0.07 ^a	0.35 \pm 0.12 ^a	0.038 (0.036)	0.104 (0.093)
Right/Left-parietal baseline	0.31 \pm 0.15	0.23 \pm 0.14	0.057 (0.068)	0.036 (0.039)
Right/Left-parietal familiar	0.30 \pm 0.11	0.21 \pm 0.08	0.073 (0.071)	0.040 (0.063)
Right/Left-parietal unfamiliar	0.33 \pm 0.13	0.24 \pm 0.12	0.103 (0.142)	0.038 (0.049)
Left frontal/Left parietal baseline	0.27 \pm 0.09	0.31 \pm 0.26	0.049 (0.028)	0.055 (0.130)
Left frontal/Left parietal familiar	0.24 \pm 0.06	0.23 \pm 0.10	0.045 (0.033)	0.047 (0.035)
Left frontal/Left parietal unfamiliar	0.25 \pm 0.07	0.22 \pm 0.11	0.056 (0.024)	0.036 (0.046)
Right frontal/Right parietal baseline	0.27 \pm 0.11	0.21 \pm 0.14	0.063 (0.053)	0.027 (0.041)
Right frontal/Right parietal familiar	0.25 \pm 0.08	0.18 \pm 0.06	0.055 (0.051)	0.030 (0.029)
Right frontal/Right parietal unfamiliar	0.25 \pm 0.09	0.18 \pm 0.06	0.058 (0.055)	0.030 (0.019)

Right/Left-frontal, coherence values from frontal lobe electrodes F6 and F5. Right/Left-temporal-parietal, coherence values from temporal-parietal lobe electrodes TP8 and TP7. Right/Left parietal, coherence values from parietal lobe electrodes P5 and P6. Left frontal/Left parietal, coherence values from frontal lobe electrode F5 and parietal lobe electrode P5. Right frontal/Right parietal, coherence values from frontal lobe electrode F6 and parietal lobe electrode P6.

^a denotes statistically significant difference between the group means at $P < 0.05$.

^b Raw data are only reported for reference; no statistical analysis was conducted on these values.

Finally, five RM-ANOVAs were conducted, one for each electrode pair at the alpha frequency, with video as a within-subject factor and group as a between-subject factor. Using Bonferroni criteria ($P < 0.01$ for five tests), a significant main effect of group was found within the right temporal-parietal/left temporal-parietal electrode pair [TYP = 0.348 ± 0.023 (mean \pm standard error, here and elsewhere), ASD = 0.193 ± 0.019 ; RM-ANOVA: $F(1, 28) = 27.6$, $P < 0.001$]. A main effect of video was found within the right frontal/left frontal electrode pair [baseline = 0.683 ± 0.033 , familiar person = 0.584 ± 0.024 , unfamiliar person = 0.595 ± 0.028 ; RM-ANOVA: $F(1.3, 39.1) = 18.7$, $P < .001$, $\varepsilon = 0.674$]. In addition, a marginally significant interaction between video and group emerged within the right frontal/left frontal electrode pair ($F(1.3, 39.1) = 5.5$, $P = 0.018$, $\varepsilon = 0.674$), such that a group difference, depending on video condition, was observed [$F(1, 29) = 5.7$, $P = 0.024$]. This finding indicates a larger z-transformed coherence at baseline vs. other conditions in the TYP group (respectively, 0.749 ± 0.051 , 0.598 ± 0.037 , 0.0614 ± 0.042), whereas there was a lack of significant

differences between baseline vs. other conditions in the ASD group (respectively, 0.616 ± 0.043 , 0.571 ± 0.032 , 0.577 ± 0.036). No group difference between familiar and unfamiliar video conditions [$F(1,29) = .222$, $P = 0.641$] was found (see Figure 1).

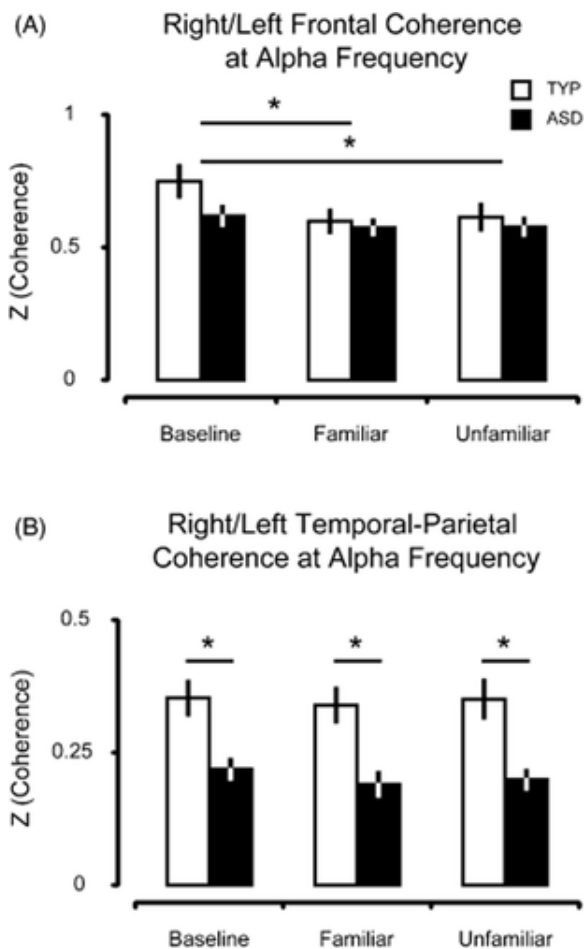


Figure 1 Fisher Z-transform estimates of coherence in alpha frequency (A) across right frontal/left frontal electrode pairs and (B) across right temporal-parietal/left temporal-parietal electrode pairs for baseline and video stimuli conditions in the ASD group (filled) and TYP group (open). Error bars indicate ± 1 standard error. * $P < 0.05$.

Lastly, utilizing the Bonferroni criteria ($P < 0.01$ for five tests), no significant main effects of group or video were found for the following electrode pairs: right parietal/left parietal, right frontal/right parietal, or left frontal/left parietal. No significant group \times video interactions were observed in these electrode pairs as well.

Discussion

This study investigated the extent to which EEG coherence, an estimate of functional neural connectivity, differed between children with ASD and typically developing children during three conditions (baseline and watching videos of a familiar and an unfamiliar person read a story). Data analysis included a data-reduction procedure that identified the frequency band (alpha) that exhibited task-relevant changes in coherence. Coherence between the right temporal-parietal/left temporal-parietal pair differentiated the groups such that children with ASD exhibited reduced coherence across all conditions as compared to the typically developing group. In addition, coherence within the right frontal/left frontal pair differentiated task conditions and groups, such that the TYP group demonstrated higher baseline coherence than the other video condition, while children

with ASD did not show higher baseline coherence than the other video conditions. No differences were found between the groups in frontal–frontal interhemispheric coherence during either video condition. Interestingly, group differences in intrahemispheric alpha coherence in the right frontal/right parietal and left frontal/left parietal electrode pairs did not reach statistical significance.

Right frontal/left frontal coherence at baseline in the typically developing children was greater than coherence in both the familiar and unfamiliar video conditions, whereas children with ASD did not show differences between the three conditions. The pattern of results suggests that children with ASD do not show differences in coherence between baseline and a task (i.e., watching a video of a person reading a story), while the typically developing children show an increased level of coherence at baseline and reduced coherence between the left and right frontal lobes during the social task. The processing of stimuli within the frontal lobes may be distributed differently during tasks than at baseline in typical development, resulting in a significant decrease in coherence from baseline (i.e., desynchronization) in response to the video-watching condition. Increased alpha power at rest has been found to be related to a suppression of alpha activity during task conditions. Increased alpha power during rest may therefore reflect active preparedness for complex tasks. Alpha suppression during a complex task may allow other networks to “take over” executive control of the actions and events required to complete the task [Knyazev, Savostyanov, & Levin, **2006**; Mathewson et al., **2012**]. If one considers that the pattern of alpha coherence observed in the typically developing group may reflect typical modulation of executive focus (i.e., demonstrating increased alpha coherence at rest, then “disengaging” for the tasks), which was not observed in the children with ASD, the lack of such modulation may reflect the inability of children with ASD to respond appropriately to complex social-behavioral tasks. Alternatively, the baseline condition may not be experienced similarly for both groups, i.e., the baseline condition may already be a “task” for the children with ASD, as the experience of coming to the laboratory, wearing the EEG cap, and being asked to look at a blank screen may have been more effortful for children with ASD than the typically developing children. In other words, the “baseline” task may be a “task” for the ASD group and explain the lack of a difference across the three conditions. In addition, this finding of decreased coherence at baseline in the ASD group mirrors similar findings of decreased connectivity in the default network in teens with ASD [Weng et al., **2010**], as well as findings of decreased activity in resting state networks incorporating “social” brain regions in adults using fMRI [von dem Hagen, Stoyanova, Baron-Cohen, & Calder, **2012**].

Additionally, it is notable that no changes were observed in right frontal/left frontal, as well as right temporal-parietal/left temporal-parietal, regions in children with ASD when presented with social stimuli (a familiar or unfamiliar person) vs. a baseline condition. Known impairments in ASD include difficulties with facial recognition/processing and attribution of mental states—key components of the “social brain” which begin to undergo changes in typical preadolescence [Blakemore, **2008**]. One possible interpretation of the finding that coherence did not differentiate between conditions for children with ASD in this sample is that the social stimuli in this study did not present as different from other aspects of the environment for these children. These findings may also suggest children with ASD are delayed or deviate from this typical neurodevelopmental trajectory, resulting in differing patterns of brain activity in processing social stimuli that were not targeted in this study or measurable with EEG.

Results also indicated that parietal-temporal coherence in the alpha frequency differentiated between the ASD and TYP groups. TYP children displayed greater coherence than children with ASD in the left and right parietal-temporal lobes regardless of video condition. As this region is considered a part of the “social brain” [Adolphs, **2001**; Brothers, **1990**], the overall decreases in coherence in children with ASD suggest that reduced functional connectivity between these regions may be associated with several of the behavioral deficits observed in this population, such as difficulties with judgment of nonverbal and verbal social cues, awareness of appropriate social boundaries, or processing others' facial expressions. These results also mirror the findings of

reduced coherence across the left and right temporal lobes at the alpha frequency reported by Coben et al. [2008].

The Role of the Corpus Callosum in Interhemispheric Connectivity

Inter- and intra-hemispheric underconnectivity has been reported in autism for long-distance connections [Just et al., 2007; Mostofsky et al., 2009], and the degree of connectivity correlates with CC size [Cherkassky, Kana, Keller, & Just, 2006]. During development, initial neural overgrowth in cortical regions has been observed in children with ASD [Courchesne & Pierce, 2005a] as has an increase in intrahemispheric cortico-cortical connections, especially in the frontal lobe [Herbert et al., 2004, referenced in Minshew & Williams, 2007]. In contrast, the CC does not exhibit a corresponding volume increase. Rather, subregions of the CC appear to have reduced volume in children and adults with ASD relative to neurotypical individuals [Brambilla et al., 2003; Verhoeven, De Cock, Lagae, & Sunaert, 2010]. These observations suggest that neural information processing deficits in ASD arise from an overgrowth of short and medium-range intrahemispheric cortico-cortical connections along with a decrease in interhemispheric connections [Minshew & Williams, 2007]. Indeed, EEG coherence is reduced following partial callosotomy [Montplaisir et al., 1990] and in people with AgCC [Nielsen, Montplaisir, & Lassonde, 1993]. Reduced coherence across the frontal lobes at the alpha frequency in ASD was also observed in the current study, consistent with the notion that the function of the anterior portion of the CC may be impaired in ASD.

Possible Mechanisms of Reduced Coherence

The current study found low EEG coherence in all three video conditions in children with ASD. Some have suggested that low coherence between two brain areas indicates that they are independent of each other [Murias et al., 2007; Nunez & Srinivasan, 2006]; however, low coherence might also be due to: (a) noise in one or both electrode signal(s); (b) nonlinearity in the transfer function from one electrode signal to the other [da Silva, Pijn, & Boeijinga, 1989]; or (3) an increase in the number of neural inputs influencing at least one of the output electrode signals. First, it is possible that local disorganization of neural connections under one or both electrodes may lead to the observation of increased signal noise. Many neurons contribute to each electrode signal and so noise might occur if the local integration of neural signals is disrupted [Ma, Beck, Latham, & Pouget, 2006; Wu, Gao, Bienenstock, Donoghue, & Black, 2006]. Notably, local over-connectivity has been reported in ASD [Minshew & Williams, 2007], especially across the frontal lobes [Courchesne & Pierce, 2005b; Just et al., 2007; but see also Sundaram et al., 2008]. Although no quantitative studies have been performed, it has been suggested that local over-connectivity impairs neural integration in autism [Minshew et al., 1997; Minshew, Sung, Jones, & Furman, 2004]. Second, if the relationship between two electrode signals is nonlinear, EEG coherence will be low. Heterogeneous conduction velocities of the neural signals may lead to nonlinear characteristics between two electrodes [da Silva et al., 1989] due to temporal delays of the neural signal. A peripheral visual attention task coupled with EEG measured latency of the peak late positive complex (LPC) across frontal electrodes, and the LPC was delayed in participants with ASD compared to typically developing participants [Townsend et al., 2001]. It is therefore possible that heterogeneous neural delays in interhemispheric connections may have contributed to reduced EEG coherence in this cohort of children with ASD. Lastly, an increase in the number of neural inputs contributing to recordings at one or both electrodes could also reduce coherence between the two electrodes. By definition, independent inputs do not correlate with each other. If an abnormally large number of inputs are present under the electrodes of interest, the recorded signals will reflect a weighted combination of those uncorrelated signals, causing degradation of the coherence measured between the two electrodes. Even if two regions have high connectivity, the presence of additional independent neural inputs could mask the coherence between the primary populations of interest. Future studies using diffusion tensor imaging to characterize white matter tracts in autism may contribute importantly to the understanding of connectivity and functional neural networks in autism and provide more

conclusive evidence that low EEG coherence between two neural regions indicates they are independent of each other.

Finally, these findings are consistent with the idea that children with ASD display more lateralized brain activity than typically developing children. Increased lateralization would imply that the two hemispheres act more independently in ASD compared to typically developing children. Greater independence would lead to decreased EEG coherence.

Summary and Limitations

It is interesting to consider that children with ASD displayed a significant deviation from neurotypical development in functional connectivity between the hemispheres in both the frontal and parietal-temporal lobes. The results of this study are consistent with findings of disordered connectivity in white matter tracts in ASD, particularly in the CC [i.e., Alexander et al., **2007**; Giedd, **2008**]. Coherence in children with ASD was not different across baseline and video-watching conditions, suggesting that they displayed a general (i.e., not task-specific) reduction of functional connectivity in comparison to typical development. In contrast, group differences in coherence within each hemisphere (between left frontal/left parietal regions and between right frontal/right parietal regions) did not reach statistical significance.

The current study was limited because the sample of children with ASD was limited to high-functioning individuals and because the sample size was rather small, which likely resulted in low statistical power. Also, in utilizing EEG for analysis, temporal accuracy and a noninvasive method of measuring brain activity were gained, which is particularly helpful in studying children with ASD. However, EEG limits findings to surface cortical activity and cannot lend insight into the deeper, subcortical connections in the brain. Finally, because the study of EEG coherence in ASD is emerging, a lack of appropriate comparison groups exists with respect to age range and task vs. baseline conditions. Future studies should address these gaps in understanding.

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