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Neural Substrates of Affective Language Processing and the Role of Autism-Like Traits in Sensitivity to Affective Language Cues

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Neural Substrates of Affective Language Processing and

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Abstract

Emotions are conveyed primarily through two channels in language: semantics and prosody. Language comprehension relies on the ability to both decode the intended semantic meaning of a phrase and to go beyond its literal meaning to understand the emotional state of a speaker. While many studies confirm the role of a left hemisphere network in processing semantic emotion, there has been debate in the field over the role of the right hemisphere in processing prosodic emotion. Some evidence suggests a preferential role for the right hemisphere, and other evidence supports a bilateral model. The relative contributions of each channel to the overall processing of affect in language are largely unexplored. Poor comprehension of emotional prosody is considered a hallmark of autism spectrum disorders and has been attributed to deficits in empathy or mind reading abilities. The present work describes two studies of affective language processing. The first used functional magnetic resonance imaging to elucidate the neural bases of processing prosodic and semantic anger. The second study probed relationships between individual differences in autism-like personality features, trait empathy, and sensitivity to anger cues in speech. Results of the first study showed a robust, distributed, bilateral network for processing angry prosody and a more modest left hemisphere network for processing angry semantics. Findings suggest the nervous system may be more tuned to prosodic cues in speech. The second study revealed a negative relationship between autism-like traits and sensitivity to prosodic valence. Consequently, some features common to autism spectrum disorder appear to confer a disadvantage in the neurobehavioral system that serves prosodic processing.

Introduction

Navigating social interactions relies heavily on the ability to detect, evaluate, and respond to the expressed emotions of others. Displays of emotion are ubiquitous, present in gestures, facial expressions, body postures, and importantly, in language. Emotions are conveyed primarily through two channels in language, semantics and prosody (Berckmoes & Vingerhoets, 2004). *Semantics* refers to meaning or the way in which abstract symbols in language map onto the real world. *Prosody* refers to the pitch, intensity, and durational qualities of speech. Accurate comprehension relies on the ability to both decode the intended semantic meaning of a phrase and to go beyond its literal meaning to understand the emotional state of a speaker.

Comprehension of a wide range of emotions is central to communication and interpersonal functioning. Ekman's foundational work on the universality of basic emotions promoted the understanding that expressions of emotions serve adaptive functions in human life (1992). Rapid and effective processing of anger cues is especially important to preservation of safety. In extreme cases, recognizing or failing to recognize another's hostility could have life or death consequences. Thus, processing of anger holds a special adaptive status. The brain's activity reflects our intuition that anger cues should be especially salient. Even in the absence of meaningful linguistic content, perception of angry vocal prosody elicits a heightened neural response; Grandjean and colleagues (2005) reported that neural activity in auditory processing brain areas is enhanced in response to nonsense speech-like stimuli that convey angry prosody. The enhancement effect is independent of voluntary attention, reflecting its significance for the success of social beings.

The neural bases of affective language processing in each of the two domains of interest, semantics and prosody, have been explored. For decades, researchers have debated the relative contributions of the cerebral hemispheres in processing emotional linguistic content. Early theories of emotion processing, connected to ideas about approach and avoidance systems in the brain, postulated that positive emotion was lateralized to the left hemisphere and negative emotion to the right (Ahern & Schwartz, 1979). While the left hemisphere is the primary seat of most language functions, findings generally support a preferential role for the right hemisphere in processing emotional tone in speech (Ley & Bryden, 1982). This may be an effect of right hemisphere lateralization of slow spectral cue processing (McGettigan & Scott, 2012). Affective prosody has been at the center of the lateralization debate and has received substantial attention in the neuroimaging literature; comparatively, there has been little work on neural substrates of affective semantics.

With respect to the neural underpinnings of affective prosody, some findings point to a right hemisphere network, while others suggest a bilateral network (Alba-Ferrara, Ellison, & Mitchell, 2012). Prosodic contour in general (as opposed to affective prosody, in particular) has been shown to rely on the right hemisphere; stripped of lexical information, prosodic pitch changes are processed by a right frontotemporal network (Tracy et al., 2011). Separating emotional from intonational prosody, Gandour et al. (2003) localized emotional prosody in the right hemisphere. Based on the results of a transcranial magnetic stimulation study conducted by Alba-Ferrara et al. (2012), the right superior temporal gyrus (STG), and not the left STG, is critical for understanding emotional prosody. Alba-Ferrara and colleagues concluded from their results that imaging data supporting a role for the left STG in processing affective prosody have not been properly interpreted. Much of the relevant work on right hemisphere lateralization for emotional prosody was integrated into a model by Wildgruber and colleagues (2009). Their model offers both bottom-up (extraction of signal properties) and top-down (emotional judgments involving memory system) routes for processing affective prosody, all in the right hemisphere, except some involvement of left inferior frontal gyrus (IFG).

Despite the traditional emphasis on the right hemisphere, evidence of a bilateral processing network for emotional prosody abounds. Sander and colleagues (2005) observed that angry prosody yielded activations in bilateral superior temporal sulci (STS) and right amygdala, whether or not the stimulus was actively attended, suggesting low-level processing in a bilateral network. Bilateral STG, including their posterolateral aspects as well as primary auditory cortices, activate in response to angry, sad, joyful, and relieved prosody (Ethofer et al., 2012). Bilateral inferior frontal areas have been implicated for secondary processing, after primary processing in the temporal lobes (Ethofer et al., 2006). Indeed, a transcranial magnetic stimulation study conducted by Hoekert and colleagues (2010) supported the equal involvement of bilateral IFG in processing angry prosody. Additional bilateral regions of activation are implicated for processing of explicitly attended emotional prosody, including right middle temporal gyrus (MTG), right planum polare, left subgenual anterior cingulate cortex, left putamen, and left amygdala (Frühholz, Ceravolo, & Grandjean, 2012). Thus, both cortical and subcortical regions participate in the proposed bilateral network. There seems to be an emerging understanding that a bilateral network underlies affective prosody and low-level acoustic features of prosody depend heavily on right hemisphere components of the network (Witteman, Heuven, & Schiller, 2012). The blue network in Figure 1 shows areas implicated in processing affective prosody, summarized from the literature reviewed here.

[Insert Figure 1 here]

Relative to prosody, affective semantics has received significantly less attention, but several functional imaging studies provide a starting point. Processing words with emotional connotations has been shown to activate left anterior superior frontal gyrus, left anterior temporal cortex, left fusiform gyrus, left posterior cingulate gyrus, and left angular gyrus (Crosson et al., 2002). Left subgenual anterior cingulate cortex plays a role in processing emotionally pleasant and unpleasant words relative to neutral words (Maddock, Garrett, & Buonocore, 2003). The retrosplenial posterior cingulate gyrus has been implicated in evaluating the emotional salience of words (Cato et al., 2004). Hearing sentences with affective semantic content, relative to sentences with neutral content, engages the left inferior frontal gyrus in addition to left posterior superior temporal sulcus and medial prefrontal areas (Beaucousin et al., 2007). Overall, the findings are left-lateralized and rely on general semantic networks that do not appear to be specific to emotional content (Binder, Desai, Graves, & Conant, 2009). The red network in Figure 1 shows areas implicated in processing affective semantics.

Our understanding of affective language processing in general, and processing of anger cues in particular, has been limited by the designs of prior studies. Most research has either examined affective prosody or affective semantics, but not both. When both have been examined in the same study, it has been difficult to disentangle their distinct neural substrates. In several such studies, participants have been instructed to attend to emotional semantics or prosody (e.g. Mitchell, Elliott, Barry, Cruttenden, & Woodruff, 2003; Vingerhoets, Berckmoes, & Stroobant, 2003). Shifting attention explicitly between the two channels of linguistic information surely impacted neural resources. The primary design limitation of studies that have incorporated both prosody and semantics is that the two channels were probed separately, rather than in a factorial design (e.g. Ethofer et al., 2006). Disentangling the relative contributions of these linguistic processing networks in the brain requires an integrated study design, in which stimuli incorporate manipulations of both prosody and semantics. Such a design was employed in Study One of the present report.

Some clinical groups, especially including people with autism spectrum disorder (ASD), exhibit difficulties with affective language processing. Individuals with ASD show deficits in expressive and receptive prosody that impact their communicative functioning (McCann, Peppé, Gibbon, O'Hare, & Rutherford, 2007). After hearing sentences spoken with emotional prosody, individuals with ASD have trouble labeling the expressed emotions and matching the sentences to facial expressions of emotions (Boucher, Lewis, & Collis, 1998; Hall, Szechtman, & Nahmias, 2003; Schultz, 2005). These deficits have been understood within the framework of ASD as a disorder of empathy or mind reading (Baron-Cohen, Jolliffe, Mortimore, & Robertson, 1997; Baron-Cohen, Leslie, & Frith, 1985). While the subtleties and complexities of language provide innumerable cues to speakers' internal experiences, individuals with ASD have particular difficulties using language to intuit the mental states of others (Tager-Flusberg, 2000).

Empathy, or the capacity to recognize and experience the mental states of others, is a central aspect of social functioning, and it is considered to be impaired in ASD (Baron-Cohen & Wheelwright, 2004). Among individuals without ASD, there is a wide range of empathic ability; some people have a strong ability to understand the experience of others, and some do not. Anecdotal data suggest that individuals who are low on trait empathy may also struggle to intuit emotional information from speech. This relationship is epitomized in ASD but likely exists on a broad continuum in the non-clinical population. In fact, the association between empathy and emotion recognition is well established; empathy is formulated as part of trait emotional intelligence (Besel & Yuille, 2010). People who are high on trait emotional intelligence are faster to identify emotional facial expressions and more responsive to mood induction than people low on emotional intelligence (Petrides & Furnham, 2003). Social and emotional language processing also relies on empathy. People with high scores on an empathy questionnaire show larger N400 ERP responses to violations of talker expectations (e.g. an adult voice saying something only a child would say) than people with low empathy scores (van den Brink et al., 2012).

In this thesis, I describe two studies of affective language processing in typically developing adults. The first study used functional magnetic resonance imaging (fMRI) to investigate the neural bases of processing angry sentences. I aimed to characterize the distinct and overlapping neuroanatomical substrates of both semantic and prosodic contributions to processing angry speech. The second study probed the relationship between autism-relevant traits and emotional judgments of angry sentences. I aimed to determine whether autism-like traits in typically developing adults contribute to individual differences in sensitivity to linguistic information that conveys anger.

Study One

Methods

Participants. Ten participants were recruited to participate in a functional magnetic resonance imaging (fMRI) study via advertisement in a university campus newspaper and by word of mouth. Two participants had to be excluded after scanning due to failed functional or structural scan acquisitions. Of the eight remaining participants, three were male and one was left-handed. All were native speakers of English. Participants ranged in age from 18 to 30 years with a mean age of 22.68 years (*SD*=3.84).

Procedure. The study was approved by the University of Connecticut Institutional Review Board, and all participants signed consent and safety screening before participating.

Participants first received training on the experimental task and the button response device in a mock scanner. Participants were placed on the bed of the MRI scanner and their heads were stabilized with foam cushions placed inside the scanner's head coil. Participants wore MRI-compatible earphones and viewed the experimental task through a mirror mounted on the head coil. In the scanner, participants were presented with a series of recorded sentences through the earphones. The sentences were declarative statements, three to five words in length, consisting of high-frequency words based on standard norms (Gilhooly & Logie, 1980; Kucera & Francis, 1967). Sentences were spoken by a female native speaker of English. They expressed semantically neutral content or angry content, and they were spoken with either neutral or angry prosody. Across conditions, sentences were matched on pitch, intensity, and duration using Praat software (Boersma & Weenink, 2013) for manipulation of the acoustic signal. Prosody was manipulated systematically such that, regardless of the semantic content, each stimulus sentence was presented separately with neutral prosody and with angry prosody. Prosodic and semantic valence (neutral versus angry) were confirmed via ratings from 11 undergraduate participants. Stimuli were only included if they were rated at the appropriate endpoints of the continuum (either 1-2 or 4-5 on a five-point scale).

Participants were not explicitly instructed to attend to affective semantics or affective prosody. To maintain and permit monitoring of attention to the task and to decrease explicit attention to affect, participants were instructed to report whether or not each stimulus sentence was about a living creature by pressing a button. The proportion of "yes" answers was set at 50%.

Four conditions resulted from crossing two levels of affective prosody (neutral and angry) with two levels of affective semantics (neutral and angry). Stimuli were presented pseudorandomly in an event-related design consisting of six runs. Each run lasted 316 seconds and contained 50 trials. There were ten trials of each condition ([a] neutral prosody/ neutral semantics; [b] neutral prosody/ angry semantics; [c] angry prosody/ neutral semantics; and [d] angry prosody/ angry semantics) as well as ten trials in which an auditory control stimulus (beep) was presented. Within each run, within each condition, trials were balanced to start at odd and even time points to yield clean sampling at effective one-second intervals. The intertrial interval was jittered between four and seven seconds. Each run also included five extra-long 12-second trials to boost power.

Data acquisition. MRI data were collected on a 3.0 Tesla Siemens Trio scanner at the Yale University School of Medicine Magnetic Resonance Research Center, with a standard birdcage head coil. Six event-related functional runs were acquired in the axial anterior commissure- posterior commissure plane using a gradient echo, single-shot echoplanar sequence (TR=2000, TE=25 [2 subjects] or 20 [6 subjects], flip angle = 60º [2 subjects] or 80º [6 subjects], 32 slices, 3.43 x 3.43 x 4 mm voxels with no gap between slices). The first five images in each functional run were discarded to account for T1 saturation effects. Three dimensional MPRAGE anatomical images were acquired for coregistration and functional localization (176 slices, 1 mm^3 isotropic voxels, TR=2530,TE=3.66, flip angle=7º). Button press reaction times were collected as a behavioral measure.

Data analysis. Reaction time data were analyzed by condition using two-factor, repeated measures ANOVA, with prosodic emotion and semantic emotion as within-subjects factors. Post-hoc paired t-tests were used to examine differences between conditions.

The MRI data were analyzed in AFNI (Cox, 1996). Preprocessing consisted of (a) slice-timing correction, (b) transformation from oblique orientation to cardinal orientation, (c) motion correction, (d) normalization to Talairach atlas space, and (e) smoothing. Following preprocessing, each subject's raw voxel intensities were converted to percent signal change to standardize blood oxygen level dependent (BOLD) activation across space and time. Next, for each condition the event time course was convolved with a gamma function to model the expected hemodynamic response (Cohen, 1997). This generated a predictor time course for each of the four conditions. For each subject, for each condition, the fit between the actual BOLD response time course at each voxel and the predicted hemodynamic response was then estimated. A two-factor, repeated measures ANOVA was conducted with prosodic emotion and semantic emotion as within-subjects factors. Prosodic emotion had two levels (neutral and angry), and semantic emotion had two levels (neutral and angry). The AlphaSim program in AFNI, which employs Monte Carlo simulations, was implemented to estimate minimum cluster sizes at various alpha thresholds. Reported significance levels are cluster-level alpha thresholds. Main effects and simple effects were analyzed at the whole brain level for suprathreshold clusters of activation. In particular, six contrasts were explored in both directions. We examined angry versus neutral prosody, angry versus neutral semantics, as well as each of these contrasts at each level of the other factor (i.e. angry versus neutral prosody for angry semantics and for neutral semantics). A cluster-corrected significance level of $p < .05$ was used as a threshold for positive results. Specific alpha levels were chosen for each contrast based on the authors' scrutiny of the anatomical specificity of activation clusters. For instance, for a given contrast, if activation clusters overlapped many distinct functional regions, the alpha threshold was lowered until sufficient separation was achieved.

Results

Behavioral Findings. Average reaction time was shortest for neutral prosody/neutral semantics (1556.05±112.41 ms), followed by neutral prosody/angry semantics (1602.55±79.01 ms), angry prosody/neutral semantics (1647.24±90.43 ms), and angry prosody/angry semantics (1655.61±81.59 ms). Average reaction time was longest for the auditory control condition (1866.04±155.63 ms). Reported values are mean ± standard deviation. Figure 2 displays reaction time results. Average reaction times differed significantly between conditions ($F(1,6)= 23.67$, $p= .002$, $\eta_p^2= .80$). Because the assumption of sphericity was violated, a Greenhouse-Geisser correction was applied to the ANOVA. Post-hoc pairwise comparisons showed that mean reaction times for all conditions differed significantly from one another, except angry prosody/neutral semantics versus angry prosody/angry semantics.

[Insert Figure 2 here]

Functional MRI Findings. Elevated BOLD response to angry prosody compared to neutral prosody was observed in eight regions: right inferior frontal gyrus (IFG) pars triangularis, right anterior superior temporal gyrus (STG)/ temporal pole, right superior temporal sulcus (STS)/ STG/ middle temporal gyrus (MTG), left STG, left and right middle occipital gyri, right posterior cingulate gyrus, and left cerebellum. Examining the prosody contrast within angry semantics, the right precuneus showed elevated BOLD response for angry compared to neutral prosody. For neutral semantics sentences only, five regions showed elevated BOLD response for angry prosody: left IFG pars triangularis, right STS, right insula, right lingual gyrus, and right cerebellum/ fusiform gyrus. Table 1 shows regions of activation and their Talairach coordinate centers.

[Insert Table 1 here]

Relative to neutral semantics, the angry semantics sentences elicited elevated BOLD response in left angular gyrus and left precuneus/ posterior cingulate gyrus. This effect seems to have been driven by the subset of sentences spoken with angry prosody, because the same regions were activated in the simple effect contrast within angry prosody sentences only. For the subset of sentences spoken with neutral prosody, no significant areas of activation were observed. Table 1 shows regions of activation.

Angry affect conveyed through both the prosodic and semantic channels yielded greater BOLD response than neutral affect. No suprathreshold elevated neural response was observed for neutral relative to angry stimuli, while many regions showed preferential activation for angry affect. Neural activation patterns included both classic language regions and other anatomical loci. An examination of beta weights for each condition in the linear model revealed a general pattern of greater differences between angry and neutral prosody, and smaller differences between angry and neutral semantics. Figure 3 illustrates the difference in BOLD effect sizes (as captured by beta weights) between the prosody and semantics contrasts.

[Insert Figure 3 here]

Because there was one left-handed participant, all contrast analyses were repeated without this participant's data. With a few exceptions, results were nearly identical without the left-handed subject. Importantly, the contrasts that yielded significant clusters of activation with the left-hander included were the same contrasts that yielded significant clusters with the left-hander excluded. Those contrasts that did not yield significant clusters still did not yield significant clusters after excluding the left-hander. For the contrast Angry >Neutral Prosody, the anterior STG/temporal pole cluster was not found. For the contrast Angry >Neutral Prosody for Neutral Semantics, the right lingual gyrus activation shifted to a cluster that encompassed the calcarine sulcus and some lingual gyrus, and an additional cluster was found in right thalamus/caudate. For Angry >Neutral Semantics, the left precuneus/PCC cluster was not found, and left angular gyrus cluster expanded to include some occipital lobe cortex. For Angry>Neutral Semantics for Angry Prosody, the left angular gyrus activation was not found. Because activation patterns were similar with and without this participant, results are presented for all subjects.

Study Two

Methods

Participants. Twenty-nine undergraduate students participated in the study for credit in an introductory psychology course. They ranged in age from 18 to 22 years, with an average age of 19 (*SD* = 0.89). The majority of participants were female (83%). All were native speakers of English.

Procedure. After signing an informed consent approved by the University of Connecticut Institutional Review Board, participants completed several measures using a laptop computer in the laboratory. All measures were programmed in SuperLab 4.5 by the first author. The participants completed the Autism Spectrum Quotient (AQ), the Empathy Quotient (EQ), and the Reading the Mind in the Eyes Test Revised (RMET) (Baron-Cohen, Wheelwright, & Jolliffe, 1997; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; Baron-Cohen & Wheelwright, 2004). These questionnaires required participants to respond to sequentially presented items by pressing buttons on the keyboard. All instructions appeared on the computer screen *and* were read aloud by a research assistant, with opportunities to ask questions or clarify the procedures. In addition to the questionnaires, participants also completed a listening task in which they were asked to rate how angry sentences seemed to them. Each participant heard 40 sentences from study one (ten from each of four conditions: [a] neutral prosody/ neutral semantics; [b] neutral prosody/ angry semantics; [c] angry prosody/ neutral semantics; and [d] angry prosody/ angry semantics) and pressed a number key to indicate a response, where “1” was not angry at all, and “7” was the angriest.

Measures. The Autism Spectrum Quotient (AQ) (Baron-Cohen, Wheelwright, Skinner, et al., 2001) is a 50-item questionnaire with five domains: social skill, attention switching, attention to detail, communication, and imagination. Respondents select one of four responses (definitely agree, slightly agree, slightly disagree, and definitely agree) for each item. To avoid response bias, approximately half of the items were designed to elicit “agree” responses from individuals who are high on autism-like traits, and half were designed to elicit “disagree” responses. Autism-like responses receive one point; responses are summed for a total score, with a maximum of 50. The established threshold for ASD is 32, with scores above that indicative of ASD. This cut-off provided a specificity of .98 and a sensitivity of .79 (Baron-Cohen, Wheelwright, Skinner, et al., 2001).

The Empathy Quotient (EQ) is a 60-item questionnaire that contains 40 empathy items (e.g. “It’s hard for me to see why some things upset people so much”) and 20 filler items. For each item, response options are: strongly agree, slightly agree, slightly disagree, and strongly disagree. To avoid response bias, approximately half of the items were designed to elicit “agree” responses from individuals who are have high trait empathy, and half were designed to elicit “disagree” responses. Strongly empathic responses receive two points and somewhat empathic responses receive one point, for a maximum of 80 points. Higher scores indicate higher trait empathy. Prior research indicates that a threshold of 30 discriminates between individuals with and without ASD, with a specificity of .88 and a sensitivity of .81 (Baron-Cohen &

Wheelwright, 2004). EQ and AQ scores are negatively correlated (Baron-Cohen & Wheelwright, 2004) and test-retest reliability is.84 (Lawrence, Shaw, Baker, Baron-Cohen, & David, 2004).

The Reading the Mind in the Eyes Test (Eyes) requires participants to match one of four complex mental state terms (e.g. arrogant, insisting, fantasizing, regretful) to a grayscale image of the eye region of a face. It is thought to measure the ability to attribute mental states to other people (Baron-Cohen, Jolliffe, et al., 1997; Baron-Cohen, Wheelwright, Hill, Raste, & Plumb, 2001). For each face, the four responses share emotional valence, which ensures that participants cannot simply respond to positive or negative affective valence. A glossary is provided to ensure that participants do not receive lower scores simply because they are unfamiliar with the definitions of words (some of which are low-frequency lexical items such as aghast, despondent, and dispirited). The total score on the Eyes is the sum of the correct responses, with a maximum of 36. Higher scores are indicative of greater mental state attribution abilities. Individuals with ASD tend to score poorly, and scores are negatively correlated with AQ scores (Baron-Cohen, Jolliffe, et al., 1997; Baron-Cohen, Wheelwright, Hill, et al., 2001).

Data analysis. Participant Likert ratings from the affective sentence judgment task were standardized on a within-subject basis: for each participant, the mean item rating and standard deviation were calculated. The difference between each item rating and the mean rating was divided by the standard deviation to obtain the standardized rating score for each item. This transformation yielded standardized Likert ratings for each of the 40 items, for each of the 29 participants. This standardization was performed to control for individual differences in the way the scale was used (i.e., the tendency to use only part of the scale).

Mean ratings were calculated for sentences with neutral prosody and angry prosody, collapsing over semantic valence. The mean rating for the neutral sentences was subtracted from the mean rating of the angry sentences to obtain a prosody difference score. The same process was repeated for angry and neutral semantics sentences, collapsing over prosodic valence, to obtain a semantics difference score. Individual difference scores reflected the perception of neutral versus angry linguistic content (in prosody and semantics). As such, this score served as an index of sensitivity to affective valence, with larger scores reflecting greater sensitivity.

Bivariate correlations between AQ, EQ, Eyes, prosody difference, and semantics difference scores were examined. Multiple linear regression analyses examined variance in prosody and semantics difference scores that was attributable to AQ, EQ, and Eyes scores. Separate regression models were tested with gender included as a predictor to determine whether gender improved model fit, given evidence of gender differences in processing emotional prosody (Schirmer, Kotz, & Friederici, 2002).

Results

The mean score on the AQ was 16.08 (*SD*= 4.89), with a range of 8 to 28. The mean score on the EQ was 46.34 (*SD*= 13.16), with a range of 26 to 69. The mean score on the Eyes was 26.48 (*SD*= 3.73), with a range of 16 to 33. Importantly, scores ranged substantially on the questionnaire measures, despite being drawn from a somewhat homogenous college sample, suggesting that the questionnaires successfully captured variation in the normal population. Mean prosody difference and semantics difference scores were 1.63 (*SD*=0.23) and 0.50 (*SD*= 0.24), respectively. Note that prosody difference scores were greater than semantics difference scores overall ($t(27)=13.90$, $p<.001$), suggesting that participants found the prosodic qualities more salient.

Table 2 displays correlations between measures. EQ scores were positively correlated with Eyes test scores (*r*= .42, *t*(27)= 2.43, *p*= .02) and negatively correlated with AQ scores (*r*= -.58, *t*(22)= -3.31, *p*= .003), indicating that those individuals who were higher in empathy tended to have better processing for facial expressions of emotion and also tended to report fewer ASD characteristics. Prosody difference scores were negatively correlated with semantics difference scores (*r*= -.67, *t*(26)=-4.60, *p*= .0001), suggesting that those subjects who heard the greatest differences between angry and neutral prosodic sentences found the angry and neutral semantics qualities to be less different. AQ scores and prosody difference scores were negatively correlated (*r*= -.44, *t*(21)= -2.26, *p*= .03; Figure 4).

[Insert Table 2 here]

[Insert Table 3 here]

[Insert Figure 4 here]

When submitted to a multiple linear regression analysis, scores on the AQ, EQ, and Eyes did not account for significant variance in prosody difference scores (R^2=.27, *F*(3,19)=2.29, *p*=.11). Similarly, scores on the AQ, EQ, and Eyes did not account for significant variance in semantics difference scores (R^2=.20, *F*(3,19)=1.55, *p*=.23). Table 3 contains results for the regression analyses. The addition of gender as a predictor did not improve model fit for either prosody difference or semantics difference scores.

Discussion

In two studies of affective language processing, we examined differences between two linguistic streams of emotional information: prosody and semantics. One study probed neural substrates of speech comprehension contrasting angry prosody and semantics; the other investigated relationships between individual differences in personality features and sensitivity to angry prosody and semantics. The principal finding of this work was the relative power of prosodic anger relative to semantic anger. Compared to semantic anger, prosodic anger (a) conferred a more substantial processing cost in reaction time, (b) yielded a more robust profile of BOLD activation, (c) engaged more brain areas across both cerebral hemispheres, and (d) was judged to be more different from neutral. Additionally, there was a significant negative relationship between scores on a measure of autism-like traits and sensitivity to angry prosody.

The findings suggest that anger communicated through prosody is more impactful than anger communicated through semantics. While the effects of angry prosody were powerful, the effects of angry semantics were subtle. This aligns with the intuitive sense that angry sounding speech is unsettling, regardless of the content. A semantically angry utterance without angry prosody does not seem to elicit the same immediate effects. The difference between participants' emotional ratings of angry and neutral prosody compared to the difference between ratings of angry and neutral semantics was substantial. Thus, subjective experiences of the emotion conveyed via the two streams converge with the neurofunctional findings of greater, more distributed BOLD response to prosody and more focused BOLD response to semantics. Reaction times were slower for semantically angry sentences than semantically neutral sentences, but reactions times were even slower for sentences spoken with angry prosody, regardless of semantic valence. Slowed reaction times reflect a processing burden associated with the angry stimuli; perhaps the adaptive significance of the signal earns anger a more rigorous and time-consuming treatment by processing resources.

Neuroanatomical findings were largely in agreement with results of prior studies. Semantic anger processing was strongly lateralized to the left hemisphere; our findings confirmed previous work that suggested a primary role for the left angular gyrus and left posterior cingulate cortex (Crosson et al., 2002). Prosodic anger engaged activation across both hemispheres of the cerebrum, as shown by previous research (e.g. Witteman et al., 2012). The observed involvement of *left* hemisphere regions in processing angry prosody supports a bilateral model as opposed to a strictly right lateralized model. In contrast to semantic processing, prosodic processing draws heavily on right hemisphere regions. This relative dependence on right hemisphere regions has likely contributed to the theory that emotional prosody is a right hemisphere function (e.g. Alba-Ferrara et al., 2012). The findings presented in the current study do not support a strict right hemisphere argument for prosody.

While many of the areas that responded to angry prosody in the present study were also observed in previous studies (bilateral temporal areas and bilateral IFG), we also found involvement of other areas. Angry prosody, relative to neutral prosody, engaged occipital areas (bilateral middle occipital gyrus and right lingual gyrus), right posterior cingulate gyrus, right insula, right precuneus, and bilateral cerebellum. The engagement of regions outside of the classic language areas in comprehension of the prosodic signal is notable. The occipital areas have been implicated in visual aspects of language processing, including word recognition (Fu, Chen, Smith, Iversen, & Matthews, 2002; Sun, Yang, Desroches, Liu, & Peng, 2011). Recruitment of visual language areas in response to angry prosody may indicate that visualization of word forms is helpful in comprehension of an emotionally important stimulus. Past studies have indicated a prominent role for the posterior cingulate gyrus in detecting emotional valence, particularly if it is associated with episodic or autobiographical memories (Maddock, Garrett, & Buonocore, 2001; Maddock et al., 2003). Emotional memory retrieval may be a vital contextual aspect of the neural response to angry prosody. The right insula is also involved in processing emotional content and interoceptive awareness (Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004; Phan, Wager, Taylor, & Liberzon, 2002). Understanding emotional information conveyed through prosody likely requires the integration of autonomic reactions in the body and cognitive evaluations of affective valence, for which the insula is ideally tuned. The precuneus has been conceptualized as a node within a network dedicated to self-representation (Lou et al., 2004). One aspect of mentally representing the self is the integration of autobiographical episodic memories and the emotional features of those memories, which could be summoned by affective cues from interlocutors. In summary, although it might seem parsimonious to interpret these areas as supplemental to the classic language areas for comprehending angry prosody, they are likely critical components of a distributed affective prosody network.

It is notable that we did not find activation for angry prosody in the amygdalae. Previous studies have highlighted the roles of both left and right amygdalae in processing of emotional prosody (Fruhholz et al., 2012; Sander et al., 2005), but our results did not reflect involvement of the subcortical emotional centers. This is likely due to methodological constraints as opposed to true lack of involvement. The amygdalae comprise relatively few MRI voxels, at an average volume of less than two cubic centimeters each (Brabec et al., 2010). Because our study did not use an *a priori* regions-of-interest approach, our cluster thresholding did not allow discovery of amygdala involvement.

We uncovered striking results in examining participants' subjective judgments of sentence angriness in Study 2. The mean prosody difference score was three times the magnitude of the mean semantics difference score, indicating an average of three times more sensitivity to angry prosody among participants. As previously noted, this fit with the reaction time and fMRI findings regarding the power of prosody and the subtlety of semantics. Interestingly, sensitivity to affective prosody (indexed by the prosody difference score), was correlated with number of autism-like traits (indexed by scores on the AQ). The relationship was in the hypothesized direction, with higher AQ scores associated with lower sensitivity to angry prosody. No relationships were found between sensitivity to angry prosody and scores on the EQ or Eyes test. This may indicate that autism-like features account for variance in affective sensitivity better than trait empathy (measured by the EQ) and mind-reading ability (measured by the Eyes test). EQ and Eyes test were hypothesized to predict sensitivity to affect because they have very direct relevance to interpreting the emotional states of others. However, our data suggest that sensitivity to affective prosody may depend more on a personality feature measured by the AQ. Participants with greater empathy or mind-reading skill did not rate angry and neutral prosody more differently than participants with less empathy or mind-reading skill.

We speculate that the AQ captured individual differences in a social communication domain that was missed by the EQ and the Eyes test. The AQ includes items that probe communication abilities (e.g. "*I frequently find that I don't know how to keep a conversation going*") and social skills (e.g. "*I find social situations easy*"). Some items in the communication subscale (e.g. "*I find it easy to 'read between the lines' when someone is talking to me*") and the social skills subscale (e.g. "*I find it difficult to work out people's intentions*") seem particularly sensitive to traits that may be related to sensitivity to prosodic cues to affect. Additionally, the AQ includes items that probe attention to detail (e.g. "*I tend to notice details that others do not*"). Individuals who endorse these items may fail to grasp the big picture. A person who tends to focus on details of speech may not comprehend a prosodic phrase. Unfortunately, the present study did not have sufficient power to conduct item-by-item analyses. Nevertheless, items like the examples provided may explain why the AQ was significantly related to sensitivity to prosodic anger. Further, the components of the AQ reviewed here may explain why only sensitivity to prosodic anger, and not sensitivity to semantic anger, was predicted by AQ scores.

Although it was surprising not to find a relationship between the affective sensitivity measures and scores on the EQ, the lack of a correlation may be explained by a close examination of the items. Many of the items seem to probe aspects of social behavior and conversational proficiency, rather than trait empathy (e.g. "*I can easily tell if someone else wants to enter a conversation*"). Items that address empathy and might be expected to predict one's ability to tune into another person's emotions (e.g. "*I find it easy to put myself in someone else's shoes*") are included but do not dominate the questionnaire. While some aspects of social and conversational proficiency are expected to be related to sensitivity to affective valence, the EQ may measure an aspect of social intelligence that is not intimately tied with emotion comprehension. In the case of the Eyes test, the lack of a hypothesized correlation with sensitivity to affective valence may be explained by its focus on complex mental states rather than primary emotions. For this reason, it may be too far removed from the notion of sensitivity to anger cues in speech.

Although our study participants were young adults without a diagnosis of ASD, our findings raise vital questions about emotional speech processing in ASD. What makes individuals with more autism-like traits less sensitive to differences in prosodic valence? Results from the current study demonstrate the behavioral and neurofunctional significance of prosodic anger cues in speech, yet sensitivity to prosody is an area of relative weakness for people with ASD and potentially for participants in the current study who endorsed more autism-like traits. Though relatively small differences in ratings of angry versus neutral prosody do not equate to functional deficits in comprehending the meaning of affective prosody, they suggest a processing difference that has negative repercussions for affective language comprehension. Some researchers have wondered about the appropriateness of using questionnaires that examine personality traits common in ASD to examine these features in typically developing people. Based on the results of a study by Murray and colleagues (2014), concern is not warranted; they found that the short form of the AQ measures similar latent traits in people with and without ASD. This supports the use of the questionnaire in the current study and suggests that our findings can be interpreted as capturing a trend that may be common to both subthreshold ASD and ASD. The notion that ASD exists on a personality continuum with the broader autism phenotype and that ASD symptoms have attenuated correlates in the broader autism phenotype is well-established (Losh, Childress, Lam, & Piven, 2008).

Several methodological limitations suggest cautious interpretation of the reported results. The fMRI study only included eight participants; however, results were relatively consistent between individuals. Even the inclusion of a left-handed participant did not alter the primary findings (see Study 1 results for a detailed summary). Traditionally, left-handed subjects are not included in fMRI studies of language because they are more likely to have right-lateralized primary language processing. According to a large imaging study by Knecht and colleagues (2000), 27% of strongly left-handed people and only 4% of strongly right-handed people have right hemisphere dominance for language. Given Knecht's findings, the probability of a left-handed individual having opposite language lateralization is low, despite being higher than the probability for right-handed individuals. In addition, there is value in capturing the full diversity of normal human brain function. To this end, some have argued against systematic exclusion of left-handed participants from neuroimaging studies (Willems, der Haegen, Fisher, & Francks, 2014). Another limitation of the present work is that two separate groups of participants were involved in Study 1 and Study 2, which prohibits the examination of neuroimaging data and personality characteristic data concurrently. For example, no conclusions can be drawn about the relationship between BOLD responses to affective prosody and scores on the AQ. It should be emphasized that the present study is not able to draw conclusions about ASD, as participants were not diagnosed with ASD. The goal was to investigate individual differences in typically developing adults. Thus, autism-like personality features have been discussed, as opposed to autism symptomatology. Finally, participants in Study 2 were mostly female, which could limit generalizability of the findings. However, when gender was included as a predictor in the linear regression models for sensitivity to affective prosody and semantics, it did not increase variance accounted for.

The results of the two studies presented here provide avenues to future work. One natural extension is to investigate other emotions besides anger using the same fMRI factorial design with prosody and semantics as factors. This would permit more general conclusions about affective language processing. The question remains whether the neurofunctional networks elucidated in the current project serve all emotions or specifically anger. Future work should investigate neural substrates and personality features in the same participants. Additionally, confirming the relationship between autism-like personality characteristics and sensitivity to affective prosody will require examining a larger sample of typically developing people with a wider range of AQ scores. Including individuals with ASD and their first-degree relatives would enable exploration of a broad spectrum of suprathreshold and subthreshold autism symptoms and their relationships to processing emotional cues in language.

Here, two studies of affective speech processing were reported. Results indicated that the prosodic information stream elicits a more substantial behavioral and neurobiological response, whereas the semantic information stream elicits a more subtle response. This suggests the nervous system may be more tuned to prosodic cues in speech. Typically developing adults with more autism-like personality characteristics were less sensitive to differences in prosodic valence, but were not less sensitive to differences in semantic valence. Consequently, some features common to ASD appear to confer a disadvantage in the neurobehavioral system that serves prosodic processing.

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Tables and Figures

Table 1. Regions of BOLD activity for contrasts of interest.

Side	**Region**	**k**	**x**	**y**	**z**	**max**	***t***
Angry Prosody > Neutral Prosody (*p*=.001)							
R	STS/STG/MTG	123	61	-24	-2	.15	5.65
R	middle occipital gyrus	71	7	-92	12	.18	5.51
L	STG	31	-62	-6	1	.15	5.58
R	IFG pars triangularis	28	48	28	1	.15	6.10
L	middle occipital gyrus	21	-27	-89	15	.10	5.59
L	cerebellum	16	-13	-71	-19	.16	6.66
R	posterior cingulate gyrus	16	0	-37	32	.11	5.42
R	anterior STG/ temporal pole	15	54	-3	-2	.14	5.56
Angry Prosody > Neutral Prosody for Angry Semantics (*p*=.005)							
R	precuneus	39	3	-44	39	.12	4.05
Angry Prosody > Neutral Prosody for Neutral Semantics (*p*=.0001)							
R	cerebellum/ fusiform gyrus	29	27	-41	-16	.18	7.98
R	lingual gyrus	17	21	-79	1	.12	8.01
L	IFG pars triangularis	15	-41	17	4.9	.14	8.07
R	STS	14	45	-30	5	.17	10.30
R	insula	13	38	-17	8	.15	7.99
Angry Semantics > Neutral Semantics (*p*=.02)							
L	angular gyrus	102	-31	-68	46	.10	3.74
L	precuneus/ posterior cingulate gyrus	60	-3	-48	25	.08	3.05
Angry Semantics > Neutral Semantics for Angry Prosody (*p*=.03)							
L	precuneus/posterior cingulate gyrus	73	-3	-54	46	.07	3.93
L	angular gyrus	70	-45	-61	42	.14	3.05

Note. Cluster-level significance values are displayed. R=right; L=left; k=cluster size in voxels; max = maximum beta value; coordinates are for maximum intensity voxel and are presented in Talairach space. Coordinates are presented in left, posterior, inferior (LPI) convention. T statistics are presented for peak voxels.

Table 2. Correlations between measures.

	AQ	**EQ**	**Eyes**	**Prosody Difference**	**Semantics Difference**
AQ	---	*t*(22)= –3.31	*t*(22)= –.60	*t*(21)= –2.26	*t*(21)= .52
EQ	–.58**	---	*t*(27)= 2.43	*t*(26)= 1.14	*t*(26)= –.43
Eyes	–.12	.42*	---	*t*(26)= 1.28	*t*(26)= –1.40
Prosody Difference	–.44*	.22	.24	---	*t*(26)= –4.60
Semantics Difference	.11	–.08	–.26	–.67****	---

*p<.05; **p<.01; ***p<.001; ****p<.0001

Note: Pearson correlation coefficients appear below the diagonal. T statistics appear above the diagonal.

Table 3. Summary of multiple linear regression results predicting prosody difference scores and semantics difference scores.

Variable	***B***	***SE***	**β**	***t***	***p***
Criterion: Prosody Difference Score, R^2= .27, $F(3,19)$=2.29, p=.11					
AQ	–.02	.01	–.45	–1.90	.07
EQ	–.002	.005	–.08	–.325	.75
Eyes	.02	.01	.28	1.35	.19
Criterion: Semantics Difference Score, R^2= .20, $F(3,19)$=1.55, p=.23					
AQ	.004	.013	.084	.34	.74
EQ	.001	.005	.05	.18	.86
Eyes	–.03	.02	–.44	–2.06	.05

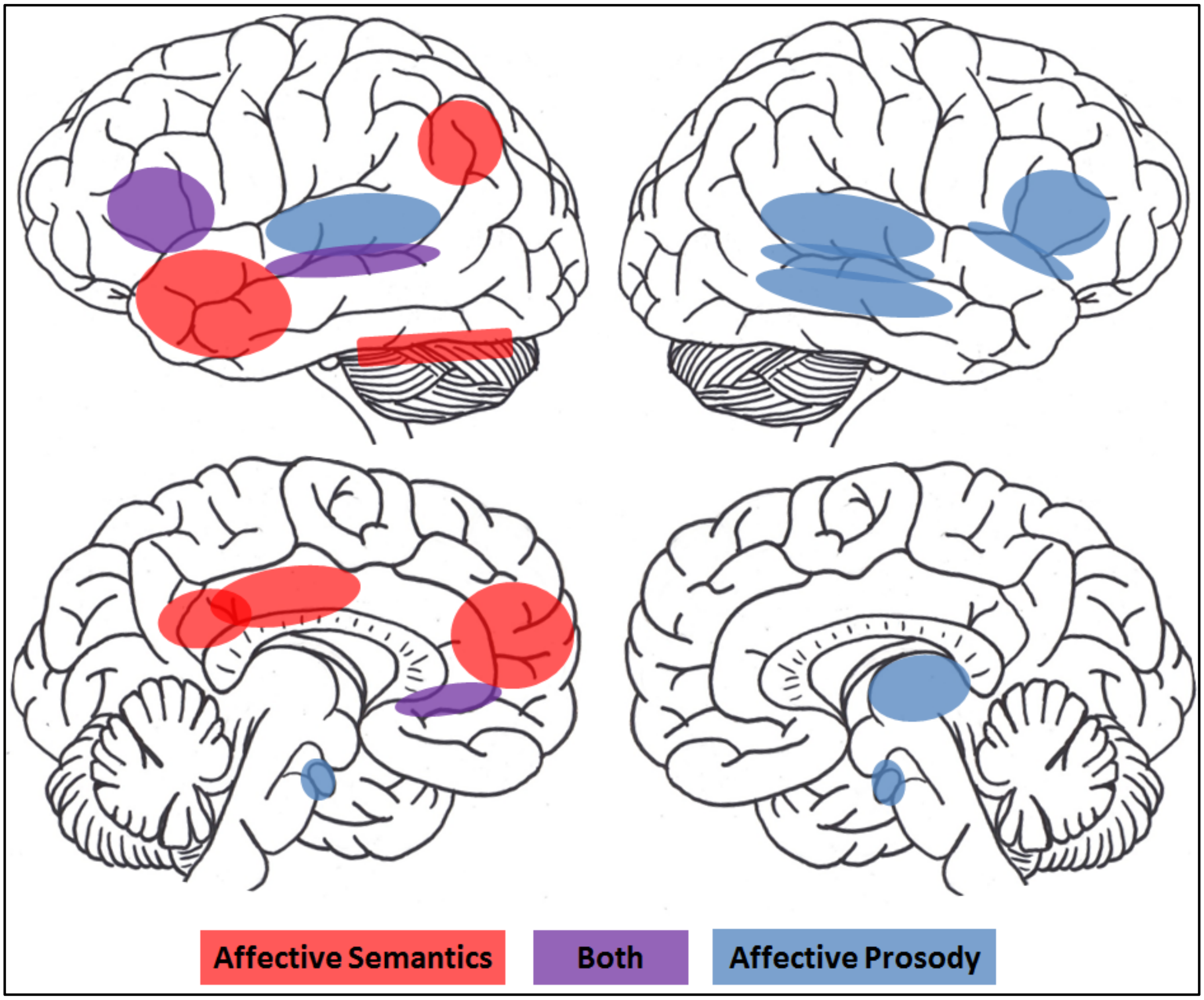

Figure 1. Affective semantics and affective prosody networks overlaid on cartoon brain. Top row shows left and right lateral views, and bottom row shows left and right medial views. Note: the rectangular overlay on the left lateral view (top left) indicates the fusiform gyrus on the inferior surface, not the inferior temporal gyrus or the cerebellum. Data are based on literature review.

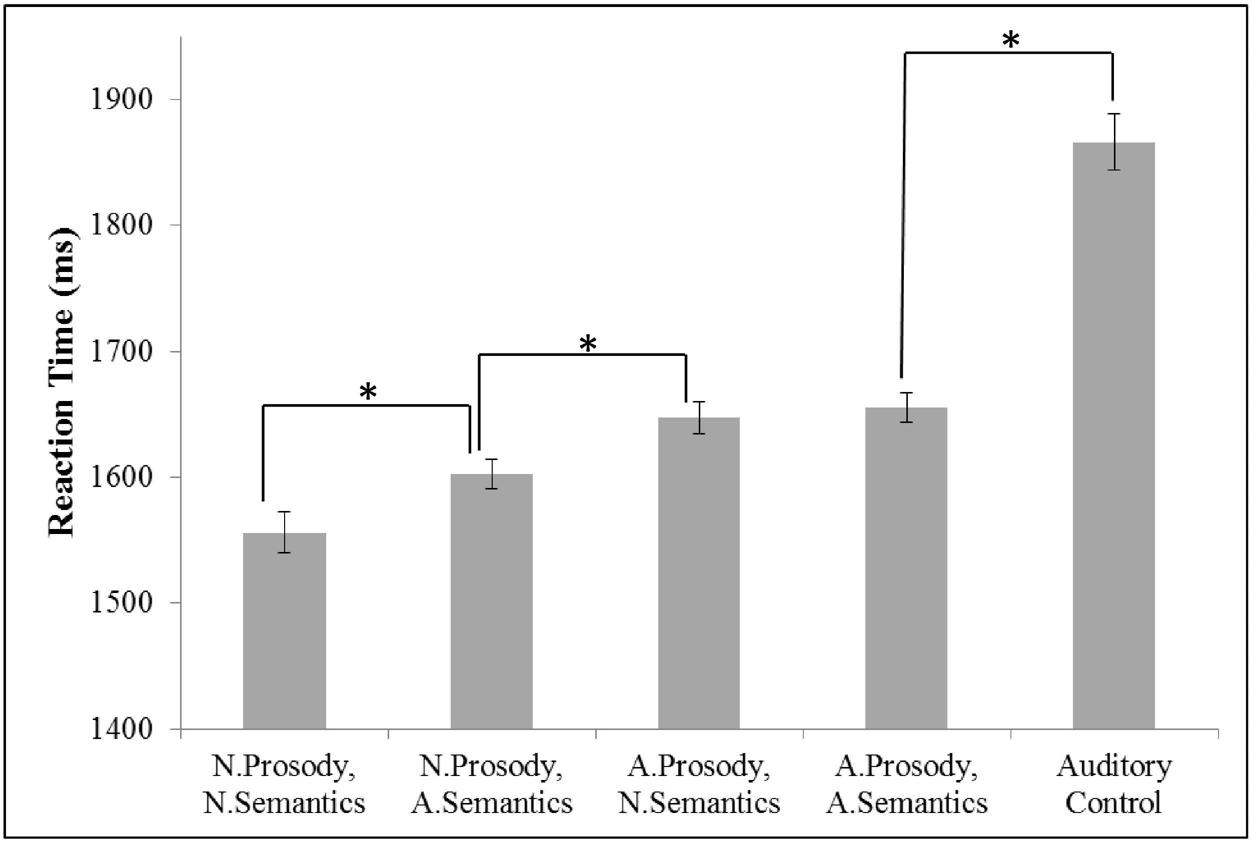

Figure 2. Mean reaction time (milliseconds) by condition. Error bars show standard error. “A” is angry; “N” is neutral. *p<.05

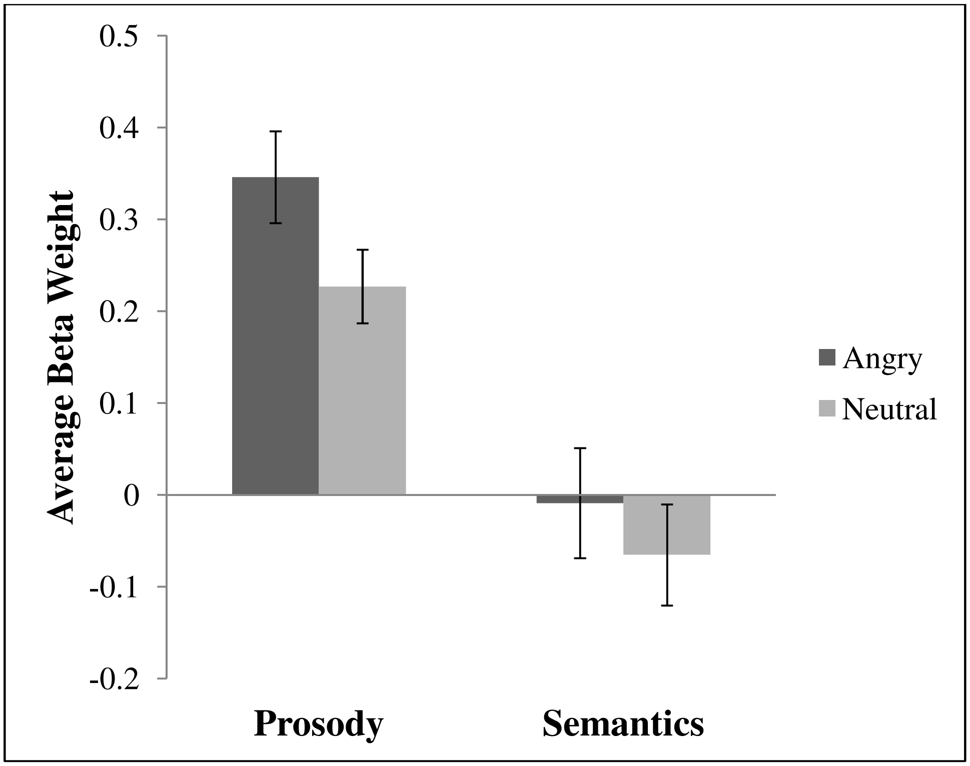

Figure 3. Magnitude of activation differences for prosody and semantics contrasts, as captured by representative average beta weights for each fMRI condition. Average beta statistics for angry and neutral prosody were extracted from the right STS/STG/MTG cluster, which was the largest cluster of significant activation for the BOLD contrast Angry Prosody > Neutral Prosody. Average values for angry and neutral semantics were extracted from the left angular gyrus cluster, which was the largest cluster of significant activation for the BOLD contrast Angry Semantics > Neutral Semantics. Error bars show standard error.

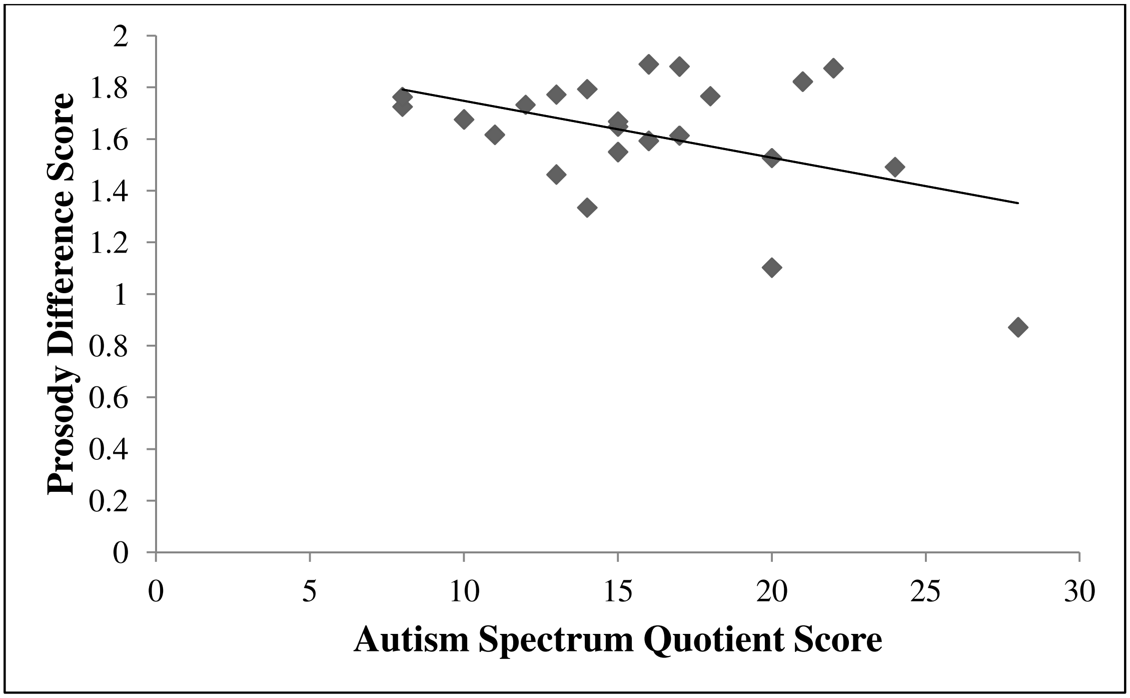

Figure 4. Standardized prosody difference score as a function of autism spectrum quotient score. Trend line shows linear relationship. R^2= .19.