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Categorical Speech Perception in Adults with Autism Spectrum Conditions

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Abstract

This study tested whether individuals with autism spectrum conditions (n=23) show enhanced discrimination of acoustic differences that signal a linguistic contrast (i.e., /g/ versus /k/ as in ‘goat’ and ‘coat’) and whether they process such differences in a less categorical fashion as compared with 23 IQ-matched typically developed adults. Tasks administered were nonverbal IQ, verbal IQ, 5 language measures, a speech perception task, and the ADOS. The speech perception task measured the discrimination of paired exemplars along the /g/-/k/ continuum. Individuals with autism spectrum conditions did not show enhanced discrimination of speech perception. Categorical speech perception was correlated with verbal ability of reading, lexical decision, and verbal IQ in individuals with ASC.

Key Words: Categorical speech perception; autism; auditory discrimination; language; phoneme.

Individuals with Autism Spectrum Conditions (ASC) exhibit perceptual processing patterns that systematically differ from those of typically developed individuals. On the one hand, individuals with ASC demonstrate enhanced perceptual performance in both auditory and visual domains, including pitch processing (Bonnel et al. 2003; Heaton 2003; Heaton 2005; Heaton et al. 1998; Heaton et al. 1999; Mottron et al. 2000; Järvinen-Pasley et al. 2008; Stewart et al. 2015) and visual pattern recognition (Plaisted et al. 1998). On the other hand, they show deficits in higher-order cognitive tasks that involve the same perceptual domains in which they show superior performance, such as the interpretation of intonational phrases or detection of emotion from faces and speech (Ashwin et al. 2007; Boraston et al. 2007; Korpilahti et al. 2007; Kujala et al. 2005; McCann and Peppé 2003). These paradoxical findings have been interpreted as manifestations of the manner in which individuals with ASC are thought to coordinate different levels of processing, namely, low levels that deal directly with the physical properties of the stimuli, and high levels where the percept of the stimuli are linked to relevant mental representations (e.g., intonational meanings, facial expressions). For instance, the style of processing associated with ASC may show: weakened integration of lower level processing with higher level processing (i.e., Weak Central Coherence; Frith 2003); an increased level of lower level processing (i.e., Enhanced Perceptual Functioning; Mottron and Burack 2001); or a lack of flexibility in ignoring prediction errors, which leads to a tendency to focus on local processing at the expense of more abstract representations of the stimuli (Van de Cruys et al. 2014).

It has been proposed that such diminished interaction between levels of processing should result in less categorical perception of stimuli (Soulières et al. 2007). Categorical perception occurs when percepts that vary continuously along a physical dimension are perceived as more distinct when they are mapped onto separate than onto the same category. A consequence of categorical perception is that a stimulus pair that spans the boundary between two categories is more discriminable than one that belongs to the same category. If the cognitive style associated with ASC means that there is a reduced role of cognitive categories in the processing of the physical properties of the stimuli, this boundary effect should be attenuated in individuals with ASC. Indeed, this is what Soulières et al. (2007) found for visual shape perception. Participants in their study were presented with tokens of ellipsis that had a constant height but varying widths. In a same-different task, participants without ASC showed heightened discriminability of stimulus pairs drawn from the midpoint region of the ellipsis continuum, the presumed location of the boundary for the two categories of ellipses, whereas individuals with ASC did not exhibit a comparable peak in discrimination around that region.

If this finding from Soulières et al. (2007) is a reflection of a broadly diminished influence of categories on perception in ASC, we expect to find similar effects in other processing domains such as speech sounds, where categorical perception has been robustly demonstrated in typically developing individuals (Liberman et al. 1957; Liberman et al. 1967). Categorical perception of speech sounds offers an important extension of the finding from ellipsis discrimination by Soulières et al. (2007) for two reasons. Firstly, humans do not normally have pre-established categories for ellipses, so the boundary-like effect observed in Soulières et al.’s participants without ASC must have come from emergent categories that they acquired through exposure to the stimulus set in the experiment. Stimulus repetition contributes to reduce discrimination of within-category differences whilst enhance between-category discrimination (Harnad 1987). Therefore one interpretation of the Soulières et al. (2007) study is that there is slower category formation in individuals with ASC. In contrast, speech sounds, such as /g/ and /k/ in *goat* and *coat*, tend to form categories that are firmly in place in adult speakers. By testing speech discrimination, we can therefore examine whether ASC affects categorical perception of pre-existing contrasts.

Secondly, if observed, diminished top-down processing in the perception of speech sounds provides one possible explanation for some of the language-related problems reported for individuals with ASC (Kjelgaard and Tager-Flusberg 2001). For a listener who has continuous or noncategorical perception of the phonetic dimension that distinguishes, say, /g/ and /k/, the between-category sound difference that separates words such as *goat* and *coat* would be less distinct. The same listener may also be riveted by within-category acoustic differences that are not relevant to such lexical contrasts; an effect that is likely to interfere with his or her linguistic processing. Reduced categorical perception offers a testable link between auditory perception skills and language functions in individuals with ASC, which to this date, has not been fully established (although see Jones et al. 2009 and Järvinen-Pasley et al. 2008).

In the current study, we examined the effects of ASC on categorical speech perception by comparing individuals with and without ASC on their discrimination of auditory stimuli taken from a continuum exemplifying the contrast between the segment /g/ and /k/. The main acoustic cue to a voicing contrast that can be heard in syllables such as /gɪ/-/kɪ/ is the temporal lag between the release burst of the consonant and the onset of the periodic wave of the following vowel: the voice-onset time (VOT). Hypothetical discrimination curves of VOT are illustrated in Figure 1. A typical discrimination curve for stimulus pairs on a VOT continuum has a peak in sensitivity around the boundary between the two sound categories - this is what would be expected from the typically developed sample and illustrated by line (a) in Figure 1. If categorical discrimination is reduced, a discrimination curve such as line (b) is hypothesised. Methodologically, the difference between these two curves can be captured by comparing the difference in discrimination level between the centre of the continuum (30/50 ms in Figure. 1) and the endpoints of the continuum (e.g, 10/30 and 50/70 ms in Figure. 1). This measure, which we call the *Categorical Discrimination Index*, should be smaller in individuals with ASC compared to that in individuals without ASC, if there is a reduction in the categorical nature of speech perception in ASC. However, given the reports of enhanced perceptual sensitivity for auditory stimuli in ASC, we need to entertain another possible scenario: Individuals with ASC may have a generally high level of discrimination ability, which causes their discrimination curve to look ‘flatter’ due to a ceiling effect. This scenario is illustrated by line (c) in Figure 1. To fully understand the characteristics of speech perception in ASC, we therefore need to examine both the general level of sensitivity (i.e., mean discrimination level) and the shape of sensitivity (i.e., the Categorical Discrimination Index). The main objective of our study was to use these measures to compare individuals with and without ASC on their discrimination curves for a /gɪ/-/kɪ/ VOT continuum.

(Figure 1 here)

The second objective of our study was to examine whether characteristics of speech perception in ASC are related to aspects of language functioning. As discussed above, less categorical perception of speech sounds may result in less clear-cut processing of the phonetic information signaling phonemic differences such as /g/ versus /k/. This may adversely affect phonological working memory capacity (e.g., remembering novel words such as *glate*, as opposed to *clate*) as well as identification of known words (e.g., recognizing *goat*, as opposed to *coat*). Deficits in phonological representations, in turn, have been associated with problems in orthographic learning and processing (Swan and Goswami 1997; Snowling 2000). Following these lines of reasoning, we investigated whether the degree to which speech sound perception is categorical is related to measures of nonword repetition, vocabulary knowledge, reading and spelling.

One caveat in studying perceptual patterns in relation to ASC is that performance in discrimination tasks can be confounded with IQ. Although a recent study has reported that perceptual ability in individuals with ASC shows no correlation with IQ (Meilleur et al. 2014), relationships between discrimination performance and IQ have been observed in typically developed adults (Deary 1994). In order to control for potential confounding effects of IQ, we recruited only adults with ASC who had been identified as being average or above in terms of their IQ and typically developing individuals who were individually matched on nonverbal-IQ.

Methods

Participants

Twenty-three adults with ASC (mean age = 25.8 years, SD = 7.2, range = 18–40 years; males = 15, females = 8) were compared with 23 nonverbal-IQ matched typically-developed adults (mean age = 28.7 years, SD = 9.8, range = 18–49 years; males = 12, females = 11). Participants were included based on a clinical diagnosis established prior to recruitment according to DSM-IV-TR criteria (APA, 2000) through multidisciplinary assessment by clinical services. In order to further characterise the participants, participants with ASC also completed the Autism Diagnostic Observation Schedule (ADOS; Lord et al. 2000) and all participants completed the Autism-Spectrum Quotient (AQ; Baron-Cohen et al. 2001) as part of the current study. Participants were classified into the ASC group if they had a diagnosis and if they met the cut-off scores on the ADOS (Lord et al. 2000) or the AQ (Woodbury-Smith et al. 2005).

Each adult with ASC was matched on a one-to-one basis to a typically-developed adult exactly on their nonverbal-IQ score using the Raven's Advanced Progressive Matrices (meaning that the participants had exactly the same nonverbal IQ score, the participants will be referred to as IQ-matched adults throughout; Raven et al. 2003). Participants were also matched as closely as possible on gender. A strategy of controlling for IQ was taken, instead of the alternative strategy of recruiting a sample of adults who varied in IQ and later controlling for IQ, due to the nature of the task and the difficulties of testing a similar paradigm across a wide IQ range.

The adults with ASC were recruited from universities and from drop-in and support centres for individuals with ASC. There was no significant difference in the number of males or females between the adults with ASC and the IQ matched adults ($\chi^2[1] = 0.81$, $p = .37$). All participants had English as their primary native language and a score above 4 on the Raven's Advanced Progressive Matrices. A score of 4 was chosen as a cut-off point because participants with a lower score might not have fully engaged with the test. None of the participants met the following exclusion criteria for the studies: history of neurological disorder, genetic or medical problems that might affect hearing, any known learning disability including speech and language impairments, and individuals who were unable to provide informed consent.

Materials

Tests of speech perception

An ABX discrimination task and an auditory lexical decision task were adapted from Stewart and Ota (2008). The ABX discrimination task was constructed using a 5-step continuum that was created using the Klatt synthesiser (Sensyn version 1.1). We created 7 base stimuli that varied in VOT from 10 ms to 70 ms in 10 ms steps and made to sound like utterances ranging from /gɪ/ to /kɪ/. All base stimuli had a duration of 250 ms and an identical rise-fall fundamental frequency contour. The VOT was manipulated by incrementally increasing the amplitude of voicing at the end of the aspiration interval from 0 to 64 dB, the amplitude of aspiration from 0 to 60 dB and the bandwidth of the first formant from 60 to 400 Hz for the duration of the aspiration interval. We then created the ABX stimuli by concatenating two base stimuli 20 ms apart (e.g., 10 and 30 ms), with an inter-stimulus interval of 1 second. The resulting ABX stimuli had VOT steps of 10-30 ms, 20-40 ms, 30-50 ms, 40-60 ms, and 50-70 ms.

The task comprised two blocks of trials. Each block consisted of 4 randomised permutations (i.e., ABA, ABB, BBA, BAB) of the 8 sets of ABX stimuli. Thus, each VOT step was tested 8 times (i.e., 4 times x 2 blocks). The practice session comprised 6 trials. Participants were required to listen to the recorded stimuli and press the numbers ‘1’ or ‘2’ on the keyboard to indicate whether the third sample was the same as the first sample or the second sample, respectively. Test time took approximately 10 minutes. Accuracy and reaction time were recorded.

We also asked whether adults with ASC would be less categorical in their discrimination of basic speech sounds. This would be observed as a less pronounced discrimination peak at the boundary in the ASC group compared to IQ-matched adults (see Figure 1 for hypothetical discrimination curves). This hypothesis was tested by an index of ‘categoricalness’, or Categorical Discrimination Index (CD Index), which we calculated by taking the mean accuracy of responses of the two endpoint stimuli (i.e., the mean of Step 10-30 ms and Step 50-70 ms) and subtracting this value from the accuracy of response at the presumed boundary in the continuum, where typically developed individuals characteristically demonstrate peak performance (i.e., boundary Step 30-50 ms). A lower CD Index indicates a smaller disparity between between-category discrimination and within-category discrimination and, thus, reduced categorical speech perception.

Auditory lexical decision

Stimuli were 48 monosyllable real words and nonwords which were read by a male speaker. The critical experimental items were pairs of words that differ by the voicing of the initial consonant such that one member was a real word in English (e.g., *golf*) and the other was not (e.g., *colf*). The place of articulation ([*p*/*b*], [*t*/*d*], and [*k*/*g*]) and voice/voiceless direction were balanced. Half of the tokens were fillers, half of which were real words and half nonwords. Each item was played once in a random order to comprise 48 unblocked trials. Participants were required to listen to the recorded stimuli and press the ‘y’ or ‘n’ keys on the keyboard to indicate whether the item they heard was a real word (“Yes”) or not a real word (“No”), respectively.

Nonverbal IQ

Test set II of Raven’s Advanced Progressive Matrices (Raven et al. 2003), which consists of 36 items, was used. Each item is multiple choice, with eight options. Answering an item correctly gives a score of 1, and incorrectly a score of 0. Therefore, the range of possible scores is 0–36. The task items were presented by a computer using the E-prime package (Psychological Software Tools, Pittsburgh, PA). We shortened the test in order to reduce participant fatigue. Rather than select a subset of items, to preserve the progressive nature of the task, we chose to present the full task with a 20 minute time limit (see Fugard et al. 2011). A high correlation is shown between this method and the full test score (r = .74; Hamel and Schmittmann 2006).

Verbal IQ

The Millhill Vocabulary Scales (Raven et al. 2003), which measure acquired verbal knowledge, were used. The test comprises two lists of words split into two sets of 34 words with the first item treated as a practice item within each set. Administered as a pen-and-paper task, the participant is required to select the synonymous word from a list of 6 possible choices. The difficulty of items increases throughout the test. A correct answer gives a score of 1 and an incorrect answer gives a score of 0, with a possible score range of 0–33.

Reading and Spelling

The Reading and Spelling components of the Wide Range Achievement Test – Third Revision (WRAT–3; Wilkinson 1993) were used. For the Reading task, participants are required to recognise and pronounce 42 words out of context. If no response is given within 10 seconds, a prompt is given to continue to the next word on the list. The Word Spelling task comprises 40 words. Each word is required to be spelled to dictation. In both cases, a correct answer gives a score of 1 and an incorrect answer gives a score of 0.

Phonological short-term memory

Phonological short-term memory was measured using a test developed from previously designed nonword repetition tasks (e.g. Grube et al. 2013). A list of nonwords comprising 20 items ranging from 4 to 8 syllables in length was played to the participants. There were 4 practice items, all of which were 4 syllables in length. The participant was required to repeat the nonword after hearing it. Two nonword repetition scores were computed for each participant: A total correct score and a nonword repetition accuracy score. The total correct score was calculated by taking the total number of correctly repeated nonwords out of 20. The nonword repetition accuracy score was calculated by taking the mean percentage of correct sounds repeated across all 20 nonwords.

Autism-Spectrum Quotient

The Autism-Spectrum Quotient (AQ; Baron-Cohen et al. 2001) is made up of 50 questions, which are divided into 5 theoretically defined subscales: *social skill*, *attention switching*, *attention to detail*, *communication*, and *imagination*. Each item has four possible answers: ‘strongly agree’, ‘agree’, ‘disagree’, and ‘strongly disagree’. We used Likert scoring (e.g., Austin 2005; Clark et al. 2013; Hoekstra et al. 2007; Stewart and Ota 2008) and included all four levels when computing scores. Item scores ranged from 1–4, so total AQ scores ranged from 50–200, and the subscores ranged from 10–40, with a higher score indicating more autistic traits.

Autism Diagnostic Observation Schedule

The Autism Diagnostic Observation Schedule (ADOS; Lord et al. 2000) is a standardised assessment of symptoms associated with the autism spectrum for autism diagnosis and classification. In this study, module 4, which is appropriate for adults who are verbally fluent, was administered. Scores are derived for diagnostic algorithms of Communication, Social Interaction, and Restricted/Stereotyped Interests, Behaviours or Activities.

Procedure

Participants were given the experimental tasks in the following order: ABX nonword discrimination, auditory lexical decision, AQ, Raven’s, Millhill, Reading, Spelling, and nonword repetition. There was missing data for 4 adults with ASC and 4 typically-developed adults for the nonword repetition task: one participant with ASC did not wish to be audio recorded which was necessary to carefully listen back and score nonwords; for the remaining 7 participants there were technical difficulties with the audio recording which meant it could not be scored. The ADOS was administered to the adults with ASC following this battery or on a separate occasion. If a separate occasion was required, this occurred no longer than 1 week subsequent to the first session. Adults were individually tested in a quiet lab or at an appropriate place at their institution and received payment for their participation. Overall test time took approximately 2 hours and 10 mins for the adults with ASC and 1 hour and 20 mins for the typically-developed adults.

The ABX nonword discrimination, auditory lexical decision, and Raven's tasks were delivered using the stimulus presentation programme E-Prime (Psychological Software Tools, Inc.). Stimuli were played on a Toshiba, Satellite Pro laptop over headphones (Edirol Audio Capture UA-3FX; Sennheiser HD 265). All the speech sounds and lexical decision task was adjusted to a comfortable volume for the individual.

Data preparation

To ensure that responses to items on each of the tasks were from those trials to which participants attended, items were removed where RTs were greater than 2.5 SD above the participant's mean latency for each auditory task. For adults with ASC, this resulted in the removal of 30 items (2.3%) from the Discrimination Task and 33 items (3.0%) from the Lexical Decision Task. For IQ-matched adults, this resulted in the removal of 51 items (3.7%) from the Discrimination Task and 35 items (2.9%) from the Lexical Decision Task.

Results

Table 1 displays the descriptive statistics of the AQ Likert Total, the Raven's, the Millhill, the number of participants who completed each task, and the language measures for the adults with ASC and the IQ-matched adults. Adults with ASC scored significantly higher on the AQ Likert Total than IQ-matched adults ($t[44] = 5.02$, $p = .000$, Cohen's d = 1.5). There was no significant difference between the groups on the Raven's, as the participants were exactly matched on this measure. There were no significant group differences on any of the other measures. One participant, who was identified as having a diagnosis of ASC, did not meet the ADOS or the AQ cut-off scores. The analyses were repeated with and without this matched pair. Inclusion or exclusion of this matched pair did not affect the significance of the results throughout except in reference to the comparison of the Categorical Discrimination Index, analyses with and without the matched pair are included only in this instance, and are outlined below. All other analyses do not include this participant and their matched control.

(Table 1 here)

Is discrimination of basic speech sounds enhanced in adults with ASC?

We tested whether individuals with ASC would show a generally higher level of VOT discrimination compared to IQ matched controls (see Figure 2). There was no significant main effect of Group ($F[1, 44] = 0.065$, $p = .80$), or Group x Step interaction ($F[4, 176] = 1.75$, $p = .14$). Response time was also assessed in order to test whether the groups approached the task in a different way (see Figure 3). There was no significant main effect of Group ($F[1, 44] = 0.03$, $p = .85$), or Group by Step interaction ($F[4, 176] = 0.68$, $p = .61$). Both groups therefore appear to process the stimuli in a similar way. This analysis did not provide support for the idea that the general level of discrimination of basic speech sounds is enhanced in adults with ASC.

(Figure 2 here)

(Figure 3 here)

Is discrimination of basic speech sounds less categorical in adults with ASC?

An independent-samples t-test revealed that adults with ASC had a lower CD Index than the IQ-matched adults. This was statistically significant with the additional matched pair ($t[46] = 2.07$, $p = .04$, $M = 0.09$, $SD = 0.31$ for adults with ASC; $M = 0.24$, $SD = 0.17$ for IQ-matched adults, Cohen's d = 0.60) and a similar effect size and a trend were found in an analysis without the additional pair ($t[44] = 1.94$, $p = .06$, $M = 0.10$, $SD = 0.31$ for adults with ASC; $M = 0.25$, $SD = 0.18$ for IQ-matched adults, Cohen's d = 0.59). A similar index was calculated for response time. There was no significant difference between the groups ($t[44] = 1.42$, $p = .16$). To verify the results of the CD Index analysis of the discrimination accuracy, we also compared the kurtoses of the accuracy scores between the two groups. The distribution of accuracy of discrimination across the 5 VOT Steps was more platykurtic for adults with ASC (Kurtosis = -0.11, $SE = 0.94$) than IQ-matched adults (*Kurtosis* = -1.19, $SE = 0.94$; $t[44] = 2.36$, $p = .02$). Therefore, these analyses provide moderate support for the idea that adults with ASC are less categorical in their discrimination of basic speech sounds.

Correlations with language measures and with symptom severity

We tested whether the CD Index correlated with performance on the language measures of Reading, Spelling, Lexical Discrimination, Vocabulary, and phonological awareness (see Table 2) in adults with ASC and IQ-matched adults. The CD Index correlated significantly with Reading, Lexical Discrimination and Vocabulary in individuals with ASC ($r = .60$, $p = .00$; $r = .45$, $p = .03$; $r = .48$, $p = .02$ respectively; Figure 4) but there were no significant correlations between the CD Index and performance in the language measures in typically developed individuals (Figure 5).

We tested whether symptom severity was correlated with the CD index in adults with ASC. There were no significant correlations between the CD Index and the AQ Likert total score (r = .35, p = .11), the ADOS Communication total score (r = -.40, p = .09), or the ADOS Social Interaction total score (r = -.41, p = .08) but there was a significant correlation between the ADOS Repetitive Interests and Stereotyped behaviours total score (r = -.50, p = .03).

(Table 2 here)

(Figure 4 here)

(Figure 5 here)

Discussion

We examined whether individuals with ASC show generally enhanced discrimination and/or reduced categorical perception of speech stimuli. Individuals with ASC did not show more accurate discrimination at any of the VOT steps in comparison with typically developed adults. This outcome contrasts with a number of previous studies which showed generally enhanced discrimination in basic auditory stimuli (Bonnel et al. 2003; Bonnel et al. 2010; Jones et al. 2009; Foxton et al. 2003; Stewart et al. 2015). It may be that the enhancement shown by individuals with ASC in these studies is specific to particular types of stimuli. The majority of studies have found enhanced discrimination for pitch, either in sinusoidal tones (Bonnel et al. 2003; Jones et al. 2009) or in speech (Heaton 2005; Heaton et al. 2008). One recent study has found that this enhanced discrimination also occurs in the temporal dimension, where participants were required to discriminate between pairs of tones and identify which pair had the longer gap between them (Stewart et al. 2015). In the current study, we asked whether these findings extended to VOT, an extension of the temporal dimension, where individuals are asked to make judgements regarding the temporal lag between the release burst of the consonant and the onset of the periodic wave of the following vowel. However, no enhanced discrimination was found at any of the VOT steps. Given that Stewart et al. (2015) used non-speech stimuli and the current study used speech-like stimuli, it may be that the enhanced discrimination effect does not apply to the discrimination of temporal acoustic features in the context of speech perception.

A second potential explanation for this discrepancy is that previous findings of enhanced discrimination in individuals with ASC may be a function of enhanced performance on nonverbal-IQ, as nonverbal-IQ is highly related to stimulus discrimination ability (Deary, 1994). Indeed, enhanced discrimination of auditory materials in ASC was not found in Kargas et al. (2015), who matched their participants with or without ASC on both age and IQ. The two groups in our study were also matched person by person on Raven’s progressive matrices, which may account for the lack of general difference in discrimination level between the ASC and the control group. A strategic decision was taken when designing the study to match the participants on nonverbal-IQ, and to recruit a sample who were relatively homogeneous for IQ. This decision means that the findings from this study are somewhat limited in their generalisability along the dimension of IQ. We suggest that this paradigm is extended to a group who vary in IQ.

We also hypothesised that individuals with ASC would show reduced categorical perception of phonemes compared to typically developed individuals. In order to assess this, we calculated a categorical discrimination index (CD Index) which assessed whether there was a difference between perception of phonemes at the edges versus the boundary and we assessed the shape of the graph. The CD Index was smaller in adults with ASC than in IQ-matched controls - this did not reach statistical significance in our sample. However, there was a trend, and the effect size was moderate. Adults with ASC did not have a noticeable peak at the boundary, and their performance was similar across the VOT steps. The discrimination function was more platykurtic for adults with ASC than for typically developing individuals. There is variability in the data with overlap between the groups, but the effect size is moderate, and worthy of discussion. The pattern of results shown suggests that the perception in individuals with ASC is less constrained by speech categories than individuals without ASC, a suggestion supported by Haesen et al. (2011) who propose that individuals with ASC focus on the local, perceptual features whereas typically developing individuals focus on socially relevant cues such as speech.The CD Index correlated with identified repetitive behaviours from the ADOS, but not with other subscales from the ADOS or with autistic traits. The lack of effect must be interpreted with caution as it may be due to a lack of variability in the ADOS and AQ scores and the lack of power.

One further concern is that the ABX discrimination task taps into attentional, language or working memory processes and is not assessing discrimination. This seems unlikely, as participant groups did not differ on reading, spelling, nonword repetition or on lexical discrimination. The ASC group were also matched one to one on IQ, which reduces the concern that this group was impaired on general cognitive ability. Crucially, the groups did not differ in their overall level of discrimination, but only in the shape of the discrimination curve.

Speech perception in individuals without ASC is optimised to differentiate linguistic categories, such as the /k/ sound in ‘coat’ and /g/ sound in ‘goat’, such that the system is relatively insensitive to the acoustic differences that do not contribute to those contrasts. In comparison, speech perception in individuals with ASC is more sensitive to acoustic differences unrelated to linguistic categories. Our findings are consistent with those of DePape et al. (2012). In one of their experiments, DePape and colleagues tested the discrimination of two pairs of foreign language sounds (Zulu consonants) by English speakers: one that maps onto two different native categories and one that maps onto a single native category. Individuals with ASC showed a smaller difference between the two-category and single-category mapping conditions than did controls. The implication is that, much like the participants in our ASC group, the individuals with ASC in DePape et al. (2012) were less influenced by their native speech categories compared to individuals without ASC. There are two main positions regarding phonemic awareness, the first, the accessibility position suggests that phonemic segments are functional and available for basic speech processing tasks from early infancy (Kuhl et al. 1992). The second position suggests that there is more gradual development over the course of childhood (Fowler 1991; Walley 1993). The current study does not test early childhood, nor does it test the relationship between discrimination of speech sounds and language development and therefore does not differentiate between these positions. Rather, the results provide evidence for a reduction in the use of existing categories in speech perception. It remains to be seen whether the effects are due to weaker or delayed category formation in ASC or a less specialised perceptual system in ASC that attends to details that are not relevant to category classification.

We assessed whether the CD Index was related to aspects of language functioning. As the CD Index got larger, performance on vocabulary (Millhill), discrimination of words versus nonwords and reading (WRAT-3 Reading) improved, indicating that the more pronounced the categorical perception, the better the performance on these tests in individuals with ASC. Between-group comparisons showed that the correlations were significantly larger in the individuals with ASC than the IQ-matched adults for both vocabulary and reading. The implication is that some of the language differences found in individuals with ASC may be due to reduced categorical perception of speech sounds. Our findings suggest the importance of further examining the link between speech processing and language functioning in ASC. Social factors, such as, social network size, the demographic make-up of the community and quality of interaction, influence linguistic skills and perception (Lev-Ari & Peperkamp 2016; Lev-Ari 2017; Ramirez-Esparza et al. 2014). It would be interesting to assess whether there are particular features of ASC due to the diagnosed differences in social interaction skills which relate to differences in speech perception.

One strength of this study is the homogeneous nature of the sample, and the one to one matching on IQ between the individuals with ASC and typically developed adults. The effect size for the CD Index comparison is moderate. To achieve a significant effect where the alpha-level is set to 5% and power to detect an effect is 80%, a sample of 76 would be required. One may then argue that our study was underpowered. This study is larger than many studies assessing perceptual processes in individuals with ASC (e.g. Soulieres et al. 2007; Bonnel et al. 2003; Bonnel et al. 2010; Järvinen-Pasley et al. 2008). This study is the first to assess categorical speech perception, and suggests that individuals with ASC do not process speech sounds in the same way as those who are typically developed. In addition, the study identifies an effect size for this important aspect of perception in ASC.

These observations spur investigations into whether children with ASC show similar differences in the categorical perception of speech sounds, at what stage this occurs, and whether this difference in the processing of speech sounds is related to later language development. We know that language skills in school-age children with Autism Spectrum Conditions are predictive of both current function and future outcome (Lord and Paul 1997; Kobayashi et al. 1992; Venter et al. 1992). Yau et al. (2016) suggest that children with ASC have developmental differences in their auditory cortex which influences their ability to process speech and non-speech sounds. If categorical perception of speech turns out to be a reliable predictor of a range of language-related processing abilities, it will provide an important source of information in identifying problems in language functioning at an early stage.

The current study sheds some light on differences in perceptual processing in individuals with ASC. Our findings suggest that it is not simply that individuals with ASC are more perceptually sensitive to the physical differences between stimuli, but that they may show qualitative differences in the way that signals are processed.

Compliance with Ethical Standards

Funding

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Conflict of interest

Authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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Figure Captions

Figure 1. Hypothetical discrimination curves for VOT. Line (a): a typical curve with a clear peak around the category boundary. Line (b): a curve with a less clear peak but with a similar general level of sensitivity as (a). Line (c): a curve with a less clear peak and a generally higher level of sensitivity than (a).

Figure 2. Discrimination of VOTs by adults with ASC and IQ-matched adults (accuracy). Error bars are standard errors.

Figure 3. Discrimination of VOTs by adults with ASC and IQ-matched adults (reaction time). Error bars are standard errors.

Figure 4. Scatterplots of the CD Index and (a) WRAT-3 Reading score, (b) Lexical discrimination score, and (c) Millhill vocabulary score for adults with ASC.

Figure 5. Scatterplots of the CD Index and (a) WRAT-3 Reading score, (b) Lexical discrimination score, and (c) Millhill vocabulary score for IQ-matched adults.

Figure 1 top

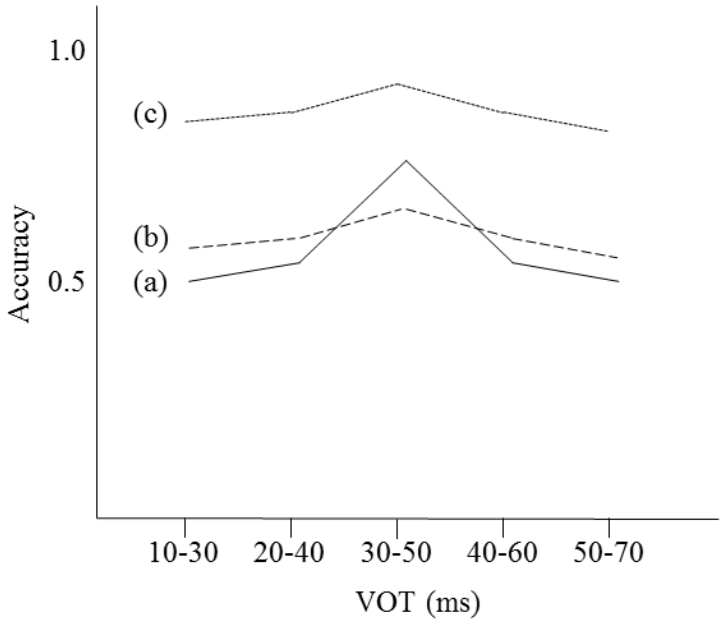
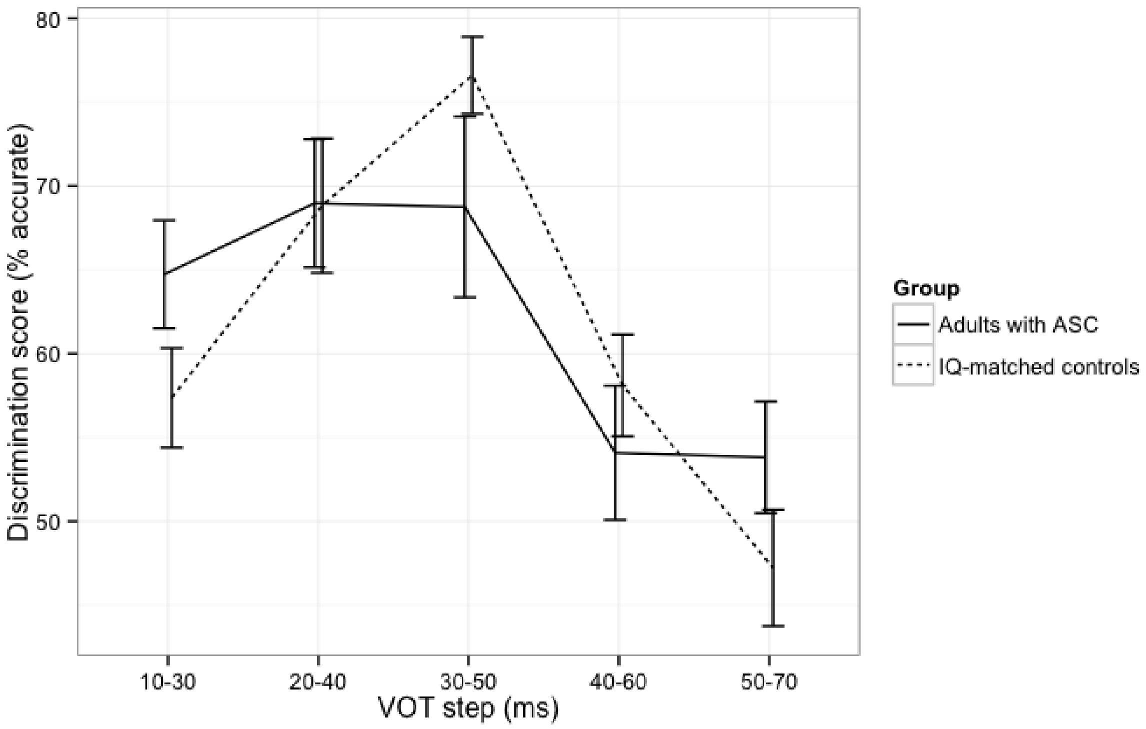


Figure 2 top



80
70
60
50
Discrimination score (% accurate)
10-30
20-40
30-50
40-60
50-70
VOT step (ms)
Group
Adults with ASC
IQ-matched controls

Figure 3 top

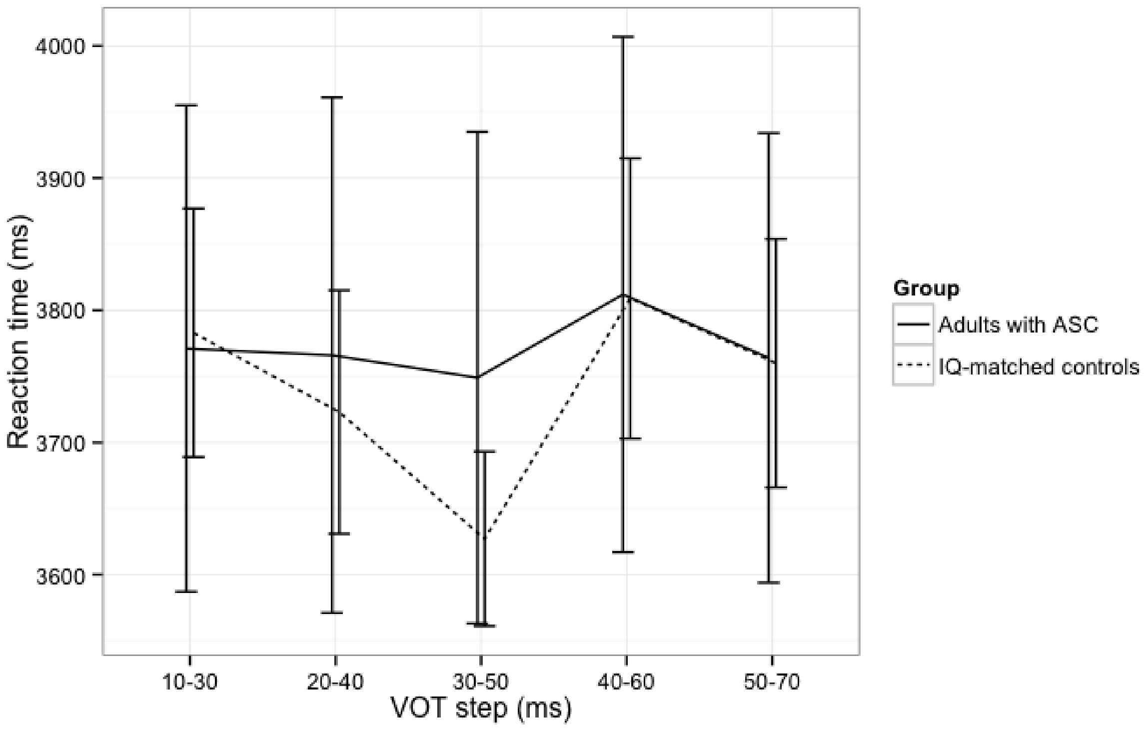

4000
3900
3800
3700
3600
Reaction time (ms)
10-30
20-40
30-50
40-60
50-70
VOT step (ms)
Group
Adults with ASC
IQ-matched controls

Figure 4 top

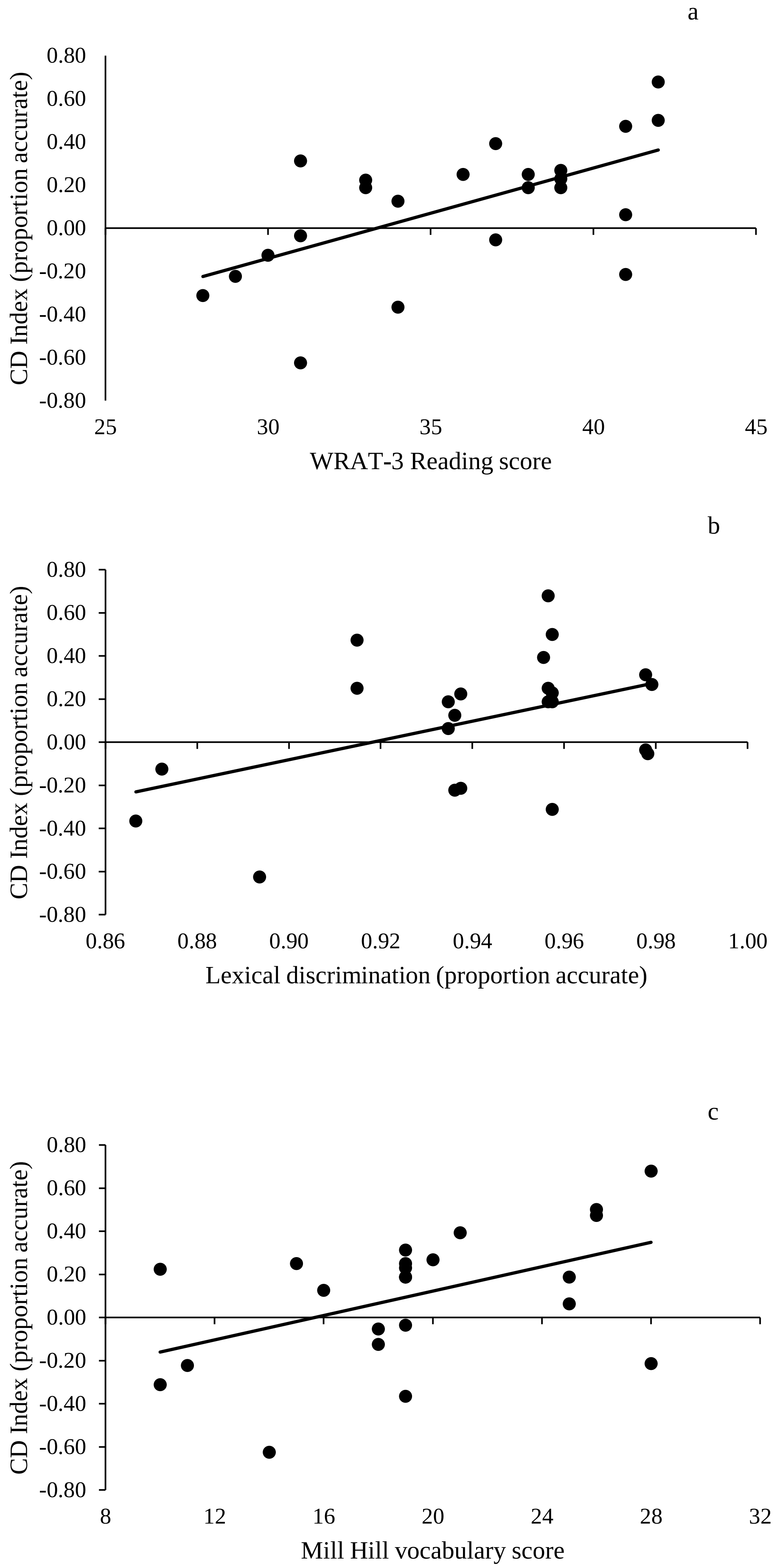

a
CD Index (proportion accurate)
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
25
30
35
40
45
WRAT-3 Reading score
b
CD Index (proportion accurate)
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
Lexical discrimination (proportion accurate)
c
CD Index (proportion accurate)
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
8
12
16
20
24
28
32
Mill Hill vocabulary score

Figure 5 top

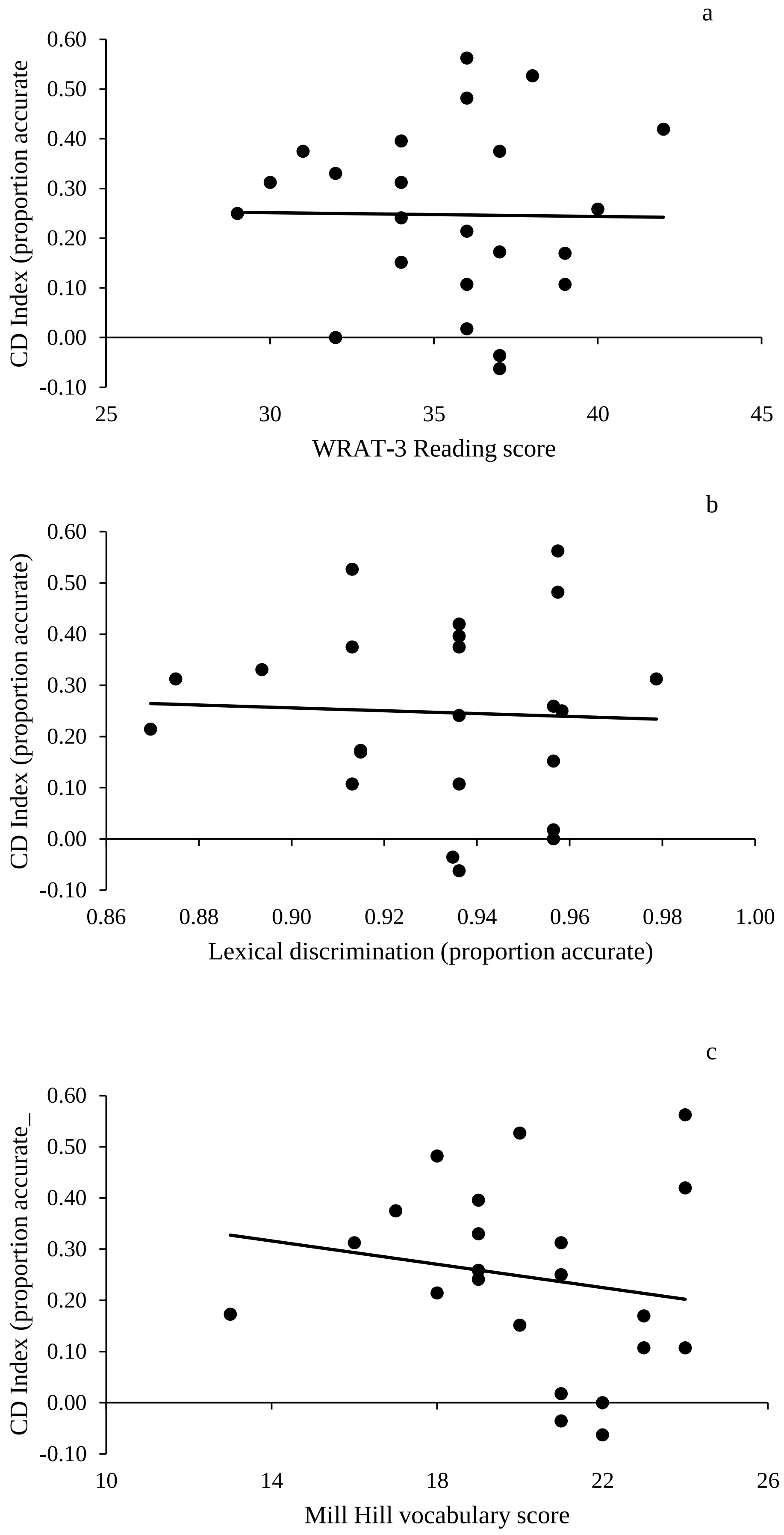

a
CD Index (proportion accurate
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
25
30
35
40
45
WRAT-3 Reading score
b
CD Index (proportion accurate)
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
Lexical discrimination (proportion accurate)
c
CD Index (proportion accurate_
10
14
18
22
26
Mill Hill vocabulary score

Table 1. Descriptive statistics of study measures for adults with ASC and IQ-matched adults

	Adults with ASC			IQ-matched adults		
	Mean (SD)	Range	*n*	Mean (SD)	Range	*n*
AQ Likert Total***	145.2 (19.9)	108 – 184	23	114.2 (21.9)	73 – 144	23
Raven's						
Raw	16.6 (5.8)	5 – 26	23	16.6 (5.8)	5 – 26	23
Standard	30.3 (19.8)	1 – 70	23	31.8 (20.8)	1 – 70	23
Millhill	19.3 (5.3)	10 – 28	23	20.0 (2.8)	13 – 24	23
Lexical discrimination (% accurate)	0.94 (0.03)	0.87 – 0.98	23	0.93 (0.03)	0.87 – 0.98	23
WRAT–3 Reading						
Raw	35.8 (4.4)	28 – 42	23	35.5 (3.2)	29 – 42	23
Standard	108.2 (8.7)	92 – 120	23	107.0 (7.5)	92 – 120	23
WRAT–3 Spelling						
Raw	30.0 (6.9)	18 – 39	23	30.6 (4.3)	22 – 36	23
Standard	106.8 (14.2)	80 – 125	23	107.6 (9.6)	89 – 119	23
NWR Average (% accurate)	0.90 (0.09)	61 – 99	19	0.90 (0.06)	0.79 – 0.98	19
NWR Total Correct	8.0 (4.8)	0 – 17	19	7.8 (3.9)	3 – 16	19

Note: AQ=Autism–Spectrum Quotient; WRAT–3=Wide Range Achievement Test – Third Revision; NWR=Nonword Repetition; $^{*}p < .001$.

Table 2. Relationships between the CD Index and the language measures for adults with ASC and IQ-matched adults

	Adults with ASC	IQ-matched adults
	r	*r*
WRAT–3 Reading	**.60****	-.01
WRAT–3 Spelling	.38	-.27
Lexical Discrimination	**.45***	-.04
Millhill	**.48***	-.18
NWR Average (% accurate)	.04	.21
NWR Total Correct	.26	.26

Note: WRAT–3=Wide Range Achievement Test – Third Revision; NWR=Nonword Repetition; all correlations, two-tailed; uncorrected for multiple comparisons by language measures; $^{*}p < .05$, $^{**}p < .01$.