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Lexical Effects on Children's Speech Processing: Individual Differences Reflected in the Autism-Spectrum Quotient (AQ)

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Abstract

Purpose: To examine whether children exhibit the same relationship that adults show between the lexical influence on phoneme identification and individual variation on the Autism-Spectrum Quotient (AQ).

Method: Data from 62 4- to 7-year-olds with no diagnosis of autism were analyzed. The main task involved identification of the initial sound in pairs of voice-onset time continua with a real word on one end and a nonword on the other (e.g., *gift-kift*, *giss-kiss*). Participants were also given the children's version of the Autism-Spectrum Quotient (AQ-child) and a second instrument related to autistic-like traits, the Social Responsiveness Scale (SRS).

Results: The lexical shift was related to the AQ (particularly to its *attention switching* subscale), but not to the SRS.

Conclusions: The size of lexical effects on children's speech perception can be predicted by AQ scores but not necessarily by other measures of autistic-like traits. The results indicate that speech perception in children manifests individual differences along some general dimension of cognitive style reflected in the AQ, possibly in relation to local/global information processing.

Keywords: *children, speech perception, Autism-Spectrum Quotient (AQ), individual differences*

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Introduction

Understanding and producing language involves the selection and integration of information from multiple sources, including auditory and visual signals, short-term and long-term memory of linguistic forms, and the language-specific organization of categories. It is therefore unsurprising that speech and language processing is subject to systematic individual differences along dimensions of wider cognitive processing such as selective attention (Francis & Nusbaum, 2002; Tipper & Baylis, 1987), suppression (Gernsbacher, 1997), and working memory (Daneman & Merikle, 1996; Frankish, 2008; Just & Carpenter, 1992). Such individual variation strongly suggests the involvement of nonsensory or 'central' factors in speech and language processing (Watson et al., 1996; Holt & Lotto, 2010).

One measure of individual variation that has been demonstrated to correlate with performance in speech processing tasks is the Autism-Spectrum Quotient (Stewart & Ota, 2009; Yu, 2010; Yu, Abrego-Collier, & Sonderegger, 2013). The Autism-Spectrum Quotient or AQ (Baron-Cohen et al., 2001) is a questionnaire designed to test the extent to which behavioral and personality traits associated with autism spectrum conditions (ASC) can be found across a broad range of populations, including people with no diagnosis of ASC. Adults without ASC but with high AQ scores (i.e., those who have more traits typically associated with ASC) are less prone to the 'Ganong effect', the tendency to shift identification of a sound to fit lexical expectations (e.g., in the lexical context *_iss*, our phoneme identification is biased toward /k/, which makes the percept a real word (*kiss*), rather than /g/, which makes the percept a nonword (*giss*) (Stewart & Ota, 2008). Women with low AQ scores make fewer adjustments in their speech perception for phonological contexts (e.g., whether a /s/ or /ʃ/ was heard before the vowel /a/ versus /u/) and talker variation (e.g., whether the talker is male or female) (Yu, 2010). Individuals with high *attention switching* subscores of the AQ tend to imitate the voice-onset time of the interlocutor more closely (Yu, Abrego-Collier, & Sonderegger, 2013).

In these studies, the linguistic tasks measure how listeners and speakers adjust their processing of acoustic signals (e.g., voice-onset time in consonants) depending on the context in which they occur, such as a potential word, phonological pattern or speaker identity. Therefore, the performance in these tasks is likely to be related to the general degree to which individuals integrate local information (e.g., the phonetic signal) and global information (e.g., the broader linguistic context), a dimension of cognitive style difference that has long been implicated in other domains including visual pattern recognition (Witkin, Dyk, Faterson, Goodenough, & Karp, 1962, Witkin & Goodenough, 1981). If so, the AQ is indexed to individual differences in local/global processing. Indeed, performance in the speech processing tasks is usually best predicted by the AQ subscale that has a strong construct-based tie to local/global information integration: *attention switching*, a measure of how strongly individuals focus their attention to a single information source at the expense of others (Stewart & Ota, 2009; Yu, 2010; Yu, Abrego-Collier, & Sonderegger, 2013). Furthermore, AQ scores correlate with other cognitive and perceptual differences that can be construed as variation in local/global information processing; for example, the recognition of embedded visual patterns (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2009; Stewart, Watson, Allcock, & Yaqoob, 2009) and taste-color integration (Clark, Hughes, Grube, & Stewart, 2013).

If the AQ is related to local/global processing, can the AQ effects found in speech processing tasks still be intrinsically connected to autistic-like traits? Such an interpretation is in keeping with theories of weak central coherence (WCC; Frith, 1989; Frith & Happé, 1994;

Happé 1996; Happé & Frith, 2006) and enhanced perceptual functioning in ASC (EPF; Mottron & Burack, 2001; Mottron et al., 2006). Under these views, bias for local processing is an integral cognitive feature of ASC, which causes either weak top-down processing (WCC) or highly developed low-level processing (EPF). Relatedly, several studies have found individuals with ASC to have enhanced identification and discrimination of isolated acoustic features such as pitch (Bonnell et al., 2003; Haesen, Boets, & Wagemans, 2011; Heaton, 2003; Heaton, Hudly, Ludlow, & Hill, 2008). It has been proposed that weak coherence or enhanced local perception is part of a normal distribution of ASC-like cognitive style that encompasses the general population (Happé & Frith, 2006; see also Baron-Cohen et al. 2001; Hoekstra et al. 2007; and Wainer et al. 2011 for the general idea that autistic traits are continuously distributed throughout the population). If this is the case, the relationship between the AQ and speech processing may involve some cognitive mechanisms that crucially underlie ASC.

Alternatively, the AQ effects in speech processing tasks may be related to a general processing style but not necessarily in conjunction with ASC. As mentioned above, in studies that find a relationship between the AQ and speech perception patterns, the *attention switching* subscore emerged as the best predictor. However, recent examination of the AQ has often failed to reliably extract *attention switching* as a subscale in the measure (Austin, 2005; Hurst et al. 2007; Kloosterman et al., 2011; Stewart & Austin, 2009). The implication is that the reported correlations between the AQ and speech processing come from a dimension of cognitive differences that is orthogonal to ASC.

In the current study, we explored these issues from a developmental perspective, focusing on the AQ-related individual differences in the lexical influence on speech perception. Previous research has shown that, like adults, children exhibit a lexical bias in their phoneme identification. For instance, both 5-year-olds and 9-year-olds shift their boundary of vowels (e.g., /ɪ/-/i/) in a continuum that has a real word on one end and a nonword on the other (e.g., *bib* vs. *beeb*) (Walley & Flege, 1999). However, little is known about the extent to which individual children differ in showing this effect and whether such differences relate to any known measure of cognitive variation. It also remains to be seen if differences in global versus local processing relate to children's speech processing, although similar individual variation has been found during infancy and childhood in visual encoding and visual pattern recognition (Stoecker, Colombo, Frick, & Allen, 1998; Chynn, Garrod, Demick, & DeVos, 1991).

The main goal of the current study was therefore to examine whether the relationship between AQ scores and the lexical effects on phoneme identification reported for adults by Stewart and Ota (2008) can also be found in children. We administered the AQ to 4- to 7-year-olds children without ASC, along with a phoneme identification task in which they classified the initial sound of a syllable in voice-onset time continua spanning the contrast between /k/ and /g/. The continua were constructed from pairs of words with lexical biases in opposite directions. For example, in the continuum created from *kiss* and *giss,* the listener's perception of the initial sound is likely to shift toward /k/ under the influence of the lexical knowledge that *kiss*, but not *giss*, is an existing word. In contrast, in the continuum created from the nonword *kift* and the real word *gift,* the perception of the initial sound is likely to shift in the other direction, toward /g/. As the initial portion of the *kiss*-*giss* continuum and the *kift*-*gift* continuum (i.e., [kɪ] - [gɪ]) is acoustically identical, the phoneme identification difference between such a continuum pair can be taken as the amount of lexically-induced shift in perception. Based on the adult results, we predicted that this perceptual shift (i.e., the Ganong effect) would be smaller in children with a high AQ score, who, by hypothesis, are less influenced by lexical information in making judgments about the phonetic dimensions of the stimuli, and therefore are more likely to respond without bias.

The relationship between the AQ and the Ganong effect may be mediated by or confounded with several attributes of the children such as their age, sex, level of auditory perception and lexical knowledge or access. If we find a link between the AQ and measures of lexical knowledge/access, then it suggests that AQ effects on the phoneme identification task can be a function of better lexical knowledge or faster lexical access rather than local/global information integration. Similarly, if we find a link between the AQ and auditory perception abilities, then it suggests that the AQ effects on the phoneme identification task can be attributed to enhanced perception rather than local/global information integration. To eliminate these possibilities, our analysis included measures of lexical knowledge/access (accuracy and latency in a lexical decision task) and auditory perception (performance in a discrimination task) as well as the children's age and sex as control variables.

A secondary goal of the study was to explore the nature of the correlation that may emerge from the experiment, particularly in order to find out whether the relevant variance in AQ scores is better understood as a manifestation of a cognitive characteristic related to ASC, or a general processing style difference in local/global integration that is unrelated to ASC. To this end, we examined the subscales of the AQ to see if the correlation involved a range of behaviors implicated in ASC-like profiles or only those that relate to local/global processing styles. Furthermore, we measured individual variance in autistic-like traits using another instrument, the Social Responsiveness Scale (Constantino & Gruber, 2005), which focuses on social behaviors associated with the ASC, such as reduction in social interaction and communication, and stereotyped patterns of interests and activities. If the individual variance in AQ reflected in speech processing differences indeed comes from a tendency toward ASC, similar relationships should be found between the SRS and the speech task performance.

Methods

Participants

The experiment was completed by a total of 81 children between the ages of 4 and 7, who were recruited from nurseries and primary schools in Edinburgh, UK. None was diagnosed with ASC. All families of the children were informed of the purpose of the study and provided written consent to participate. Of these children, 62 passed the 'fidelity check' (described below) and contributed data that were further analyzed. The resulting participant pool ranged in age from 4 years and 2 months to 7 years and 7 months, with a mean of 5 years and 11 months (fifteen 4-year-olds, fourteen 5-year-olds, seventeen 6-year-olds, and sixteen 7-year-olds). Thirty-four of them were male and 28 were female.

Materials

Phoneme identification. The materials for the phoneme identification task consisted of three pairs of word-to-nonword and nonword-to-word voice onset time (VOT) continua along the /k/-/g/ contrast. One pair was based on the words *kiss* and *gift*, with one continuum ranging from the real word *kiss* to the nonword *giss* and the other from the nonword *kift* to the real word *gift*. The other two continuum pairs were based on *keep* (to *geep*) and *geese* (to *keese*), and *kept* (to *gept*) and *guess* (to *kuess*). These continua were produced by digitally cross-splicing naturally spoken tokens (e.g., *gift*, *kift*, *kiss* and *giss*) read by a female speaker of Standard Scottish English, and recorded at a sampling rate of 48 kHz. The initial proportions of the /k/-initial nonword and /g/-initial real word (e.g., *kift* and *gift*) were replaced by those with the same onset (e.g., *kiss* and *giss*, respectively) such that the endpoint pairs were acoustically identical up to 100 ms after the onset. These tokens were then cross-spliced to produce pairs of 7-point continua with equal steps, with minor adjustments made to enable splicing at zero-crossings. The VOTs of the stimuli are given in Table 1. The stimuli were down-sampled to 44 kHz and mounted on a stimulus presentation programme (E-Prime).

<Insert Table 1 around here>

In order to make the phoneme identification task more accessible to the young participants, visual stimuli were created to anchor the target sounds /k/ and /g/. The sound /k/ was associated with a kangaroo called 'Keeka' (/kikə/) and the sound /g/ with a gorilla called 'Geega' (/gigə/). These animated characters appeared next to each other with equal distance from the center of the screen, and moved in reaction to the children's response as described in the procedure section. A screen shot of these characters is available in the Supplementary Materials section.

Auditory lexical decision. This task was used to measure the general speed of word retrieval involving voice contrasts in the initial position. The stimuli were 48 recorded tokens of real words and nonwords, read by the same female speaker who provided the base tokens for the phoneme identification task. Half the tokens were experimental items that were designed to be similar to the word-nonword pairs in the identification task. They were all monosyllabic words with an initial stop onset, with the real word members matched for frequency with the real words used in the phoneme identification task, based on lemma counts in the British National Corpus (BNC Consortium, 2007). The stimulus set was balanced for place of articulation ([p/b], [t/d], [k/g]) and the voice/voiceless direction. The mean age of acquisition of these words was 4.1 years according to estimates from Kuperman, Stadthagen-Gonzalez and Brysbaert (2012). All experimental items are given in the Supplementary Materials section. The remaining 24 tokens were fillers, half of which were real words and the other half nonwords. They were all monosyllabic words beginning in a singleton consonant (e.g., *cheese*, *muft*) or a consonant cluster (e.g., *bring*, *fleague*).

Nonword XAB discrimination. This task was used to measure children's perceptual sensitivity to VOT differences. The auditory stimuli for the XAB discrimination task were generated from the initial 100ms portions of the endpoint stimuli of the *kiss*-*gift* series used in the phoneme identification task. These base stimuli were cross-spliced to yield a [kɪ]-[gɪ] continuum that ranged in VOT from 10 ms to 70 ms with a step size of 10 ms. As a pilot study indicated that many young children find it difficult to discriminate a 20 ms difference in these stimuli, the XAB materials were created by concatenating two stimuli 30 ms apart (e.g., 10 and 40 ms) with an inter-stimulus interval of 1 s. All four permutations for each combination (i.e., AAB, ABA, BAB, and BBA) were included in the stimulus set.

To make the XAB task accessible to the young participants, a visual paradigm was used to anchor the X, A and B stimuli to three animated frogs. A large light-green frog ('mother' frog) appeared in the center of the screen, flanked by two small frogs ('baby' frogs), one in orange and the other in dark green. The X auditory stimulus was synchronized with a croaking movement of the mother frog and the A/B stimuli with the croaking of each of the two baby frogs. A screen shot of the animation is available in the Supplementary Materials section.

AQ-Child. The first instrument used to measure traits associated with ASC was a version of the AQ adapted for children 4-11 years of age (AQ-Child; Auyeung, Baron-Cohen, Wheelwright & Allison, 2008). The AQ-Child is a parent-report questionnaire with 50 items designed to assess five areas: *social skills* ("Good at social chit-chat"), *attention switching* ("Can switch back after an interruption"), *attention to detail* ("Notices numbers of strings of information"), *communication* ("Does not let others to get a word in edgeways") and *imagination* ("Finds making up stories easy"). Prior research shows that three of the original 50 items have questionable validity (Auyeung et al., 2008). These items, all from the *attention to detail* subscale, were therefore excluded from the analysis. The questionnaire items were rated by the parent on a 4-point Likert scale including 'definitely agree' (3), 'slightly agree' (2), 'slightly disagree' (1) and 'definitely disagree' (0), with reverse scoring applied to polarity-reversed items. The total range of possible scores on the AQ-Child is 0 to 147 (after the exclusion of the three items mentioned above), where a higher score indicates more 'autistic-like' traits.

SRS. The second measure of autistic-like traits was the Social Responsiveness Scale (SRS; Constantino & Gruber, 2005). The SRS is a 65-item parent/teacher-report questionnaire designed to measure ASC-related behaviors in individuals from 4 to 18 years of age, with a particular focus on the ability to engage in an emotionally appropriate social interaction with other individuals. Like the AQ-Child, items in the SRS are broken down to 5 components: *social awareness* ("Knows when he/she is too close to someone or invading someone's space"), *social information processing* ("Concentrates too much on parts of things rather than 'seeing the whole picture', for example, if asked to describe what happened in a story, child may talk only about the kind of clothes the characters were wearing"), *capacity for reciprocal social responses* ("When under stress, child seems to go on 'auto-pilot'"), *social anxiety/avoidance* ("Does not join group activities unless told to do so"), and *characteristic autistic preoccupations/traits* ("Has repetitive, odd behaviors, such as hand flapping or rocking"). Responses are scored on a Likert scale including 'never true' (0), 'sometimes true' (1), 'often true' (2) and 'almost always true' (3), with appropriate reverse coding. The overall score can range from 0 to 195, with a score of 95 to best discriminate children with or without ASC (Constantino & Gruber, 2005).

Procedure

Each child was tested separately in a quiet room by an experimenter, who administered the three experimental tasks on a computer. The child wore a headset to listen to the recorded material. The phoneme identification task was given first, followed by the lexical decision task and the XAB task. As an incentive, the child received a sticker after completing each task. The AQ-Child and the SRS were completed by the parent(s) of each child. Procedural details of the three experimental tasks are given below.

Phoneme identification. The child first saw a video in which the two animated characters introduced themselves: "Hi! I'm Geega the gorilla. I like the sound /g/, like in *goat* and *giggle*. Hi! I'm Keeka the kangaroo. I like the sound /k/, like in *kitten* and *kick*." The voice-over was provided by the same person who read the base test stimuli for the identification task. The experimenter then asked the child what kind of sound Geega the gorilla and Keeka the kangaroo liked respectively. If the child responded correctly, the experimenter proceeded to the practice session. If not, she played the introduction sequence again. The replay was done only once. The practice session consisted of four items: *cat*, *gas*, *gat* and *cas,* with the latter two items created by cross-splicing the first two. The children were told that they were to choose the gorilla if they heard something that started with the sound /g/, and choose the kangaroo if they heard something that started with the sound /k/. Children responded by pressing one of the two buttons on a serial response box that had a print out of the two characters attached. When a button was pressed, the corresponding character was highlighted by a changing background and a sound effect was played. This sequence took 1 s, after which the next stimulus was played. Upon completion of the practice session, the experimenter once again checked with the child if they had understood the task before starting the main task. The main task contained 42 unique stimuli (3 pairs of 7 step continua) repeated twice each, for a total of 84 trials. The trials were broken into 4 blocks, with each unique stimulus played once within the first two blocks and once in the second two blocks. Trials were randomized within each block. Children were allowed to take a brief break between blocks.

Lexical decision task. Prior to the practice session, the experimenter explained to the child that their task was to press the designated 'yes' button on the response box if they heard a real word and the 'no' button if they heard a made-up word. Each trial began with a stand-by visual stimulus (a line drawing of a girl listening to a portable recorder), which lasted for 500 ms. The stimulus was then played. When the button on the serial response box was pressed, a picture of a big smiley face with a thumbs up was shown for 750 ms regardless of the accuracy of the response. The practice session consisted of four items: *kiss, keep, gat* and *geep*. The experimenter checked the child's comprehension of the task requirements and, if necessary, explained the task again before moving on to the main items. The main task contained 48 unblocked randomized trials.

XAB task. Prior to the practice session, the experimenter explained to the child that there are three frogs: mother frog and two baby frogs. Mother frog croaks first, and the two baby frogs try to croak just like mother frog. Their task was to choose the baby frog that sounded exactly like mother frog for that round. The child made the response by pressing one of the two buttons on the response box that were marked with the pictures of the baby frogs. No feedback was given, and the next item set was played 1 s after the button was pressed. The experiment started with a practice session consisting of four XAB items with VOTs of 10/10/70ms, 10/70/10ms, 70/10/70ms and 70/70/10ms, respectively. The main session consisted of two blocks, each containing a randomized set of 16 unique trials. Children were allowed to take a short break between the blocks.

Results

Fidelity check

In order to exclude from the main analysis children who failed to understand the procedural requirements of the phoneme identification task, signal detection theory was used to measure the participants' fidelity to the voice distinction in the onset of the stimuli (i.e., /k/

vs. /g/), the distinction to which the children were meant to be responding. For each child, a d-prime (d') value adjusted for two-alternative forced choice was calculated on the response data at the two ends of each continuum (e.g., 'kiss' vs. 'giss'), where the VOT values matched those of the naturally spoken tokens (e.g., of 'kiss' and 'gift'). The d' values ranged from 3.83 (consistently selecting the correct sound) to –0.121 (slightly biased to pick the wrong sound). Children with a d' parameter below 0.2 showed little sensitivity to the onset difference of these end-of-continuum stimuli and were likely to have misunderstood the nature of the task. These children (N =19) were excluded from further analysis. As a group, the excluded children (mean: 5 years and 2 months) were younger than the included children (mean: 5 years and 11 months) [$F(1, 79) = 9.38$, $p < 0.01$]. Their mean AQ and SRS scores were lower (35.1 and 19.9, respectively) than those of the included children (37.6 and 23.6, respectively), but these differences were not statistically significance [AQ: $F(1, 79) = 0.80$, n.s.; SRS: $F(1, 79) = 0.84$, n.s.].

Main analysis

For the auditory discrimination task, trials with reaction times longer than 2.5 standard deviations above each participant's mean latency were excluded from the analysis (3.4% of the data). Discrimination level was indexed to the mean accuracy for the 10/40 ms and 20/50 ms XAB stimuli, where the correct response rates were the highest. The reaction times in the lexical decision task were based on correct responses only, and did not include trials with reaction times longer than 2.5 standard deviations above each participant's mean latency (3.2% of the data).

Descriptive statistics for the independent factors are summarized in Table 2. The score distributions for the AQ (M = 37.6, SD = 16.4) and the SRS (M = 23.6, SD = 16.6) were typical of children with no diagnosis of ASC. By way of comparison, the control participants in Auyeung et al.'s (2008) study of the AQ-Child had a mean of 41.7 and a standard deviation of 18.6. The control participants in Constantino and Todd's (2003) examination of the SRS had a mean of 29.9 and a standard deviation of 15.0.

<Insert Table 2 around here>

Correlations among the main independent factors and among the AQ and SRS subscales are given in Tables 3 and 4, respectively. There was a strong positive correlation between the overall AQ and SRS scores, confirming the high convergent validity of the two measures (see Armstrong & Iarocci, 2013). As can be seen in Table 4, correlations were particularly high between AQ's *social skills* and *communication* subscales on one hand and SRS's *social information processing* and *capacity for reciprocal social responses* subscales. There was also a negative correlation between the children's age and their speed of lexical decision, presumably in reflection of the age-related familiarity with the lexical items. Subscales of the two autistic trait measures were highly inter-related except for the *attention to detail* AQ subscale, which did not correlate with any other AQ subscale scores.

<Insert Tables 3 and 4 around here>

We first examined the extent to which lexical information generally affected the response pattern in the phoneme identification task. Figure 1 shows the mean /g/-response rate for the two types of continua at each VOT step. A two-way repeated-measures ANOVA was performed on the mean proportion of /g/ responses as the dependent factor, and Condition (word-to-nonword vs. nonword-to-word) and VOT Step (1 through 7) as independent factors. A significant main effect of Condition [$F(1, 61) = 34.70$, $p < .001$] was found, as well as a main effect of Step [$F(6, 366)=73.78$, $p < .001$]. There was also a marginal interaction between the two sources [$F(6, 366) = 1.90$, $p = .08$]. Items in the word-to-nonword continua (e.g., *gift-kift*) were more likely to be judged as being /g/-initial than the VOT-corresponding items in the nonword-to-word continua (e.g., *giss-kiss*), although this tendency was less pronounced in the short VOT end of the continua. There was a bias toward

/g/ responses (mean /g/ response rate = 64.6%), which may have been an effect of cross-splicing of the stimuli or the attractiveness of the gorilla character in the animation. This response bias did not differ by age [$F(3, 58) = 2.36$, n.s.] or sex [$F(1, 60) = 0.07$, n.s.]. Despite this, the result clearly demonstrates a Ganong effect in this group of children.

<Insert Figure 1 around here>

In order to examine how the responses in the identification task may be related to the AQ and SRS scores, we used mixed-effects models with a logistic link function. The models were fitted with the *lmer4* package of R (R Development Core Team, 2011). As the AQ and the SRS were highly correlated with each other, separate models were built for these measures. For both models, the dependent variable was the participant's response (coded 1 for /g/ and 0 for /k/) indicating the likelihood of /g/ response. Each model contained four main effects: Condition (word to non-word versus nonword to word), Step (1 through 7, where 1 corresponded to the shortest VOT), Age of participant (in days, to avoid false convergence), and either the AQ or SRS. AQ/SRS scores, Age, and Steps were centered. Condition was coded numerically as -0.5 (word-to-nonword) and 0.5 (nonword-to-word). The model also contained the full set of interactions between Step, Condition, Age and AQ/SRS. In addition, the model contained a random by-participant intercept and three by-participant random slopes, for Trial Block, Condition, and Continuum Words (*gift-kift* vs. *geese-keep* vs. *guess-kept*). This model was obtained through backward elimination from an initial model that additionally contained Sex (male versus female), Discrimination (mean accuracy), and Lexical Decision (reaction time) as predictors, none of which was significant in the larger models and which were eliminated from the final model.

The results of the model including the AQ are summarized in Table 5. Positive β values indicate that a higher value in a predictor makes a /g/ response more likely. Confirming the results of the ANOVA reported above, we found significant main effects of

Step and Condition. The odds of a child giving a /g/ response decrease as a function of an increase in the VOT step and also when the stimuli are taken from nonword-to-word continua (e.g., *giss-kiss*) compared to word-to-nonword continua (e.g., *gift-kift*). Both Step and Condition show a significant interaction with Age such that older children exhibit larger differences in their response pattern depending on the VOT and lexical status of the stimuli. The interaction between Age and Step and that between Age and Condition are illustrated in Figures 2 and 3, respectively. Most importantly, there is also a significant interaction between AQ and Condition. The regression weight for the interaction is slightly positive ($\beta = 0.0207$, or odds ratio 1.02), counteracting the much larger main effect of Condition in the opposite direction ($\beta = -1.341$, or odds ratio 0.26). In other words, as can be seen in Figure 4, the difference in the proportion of /g/ responses due to the lexical status of the stimuli is attenuated in children with high AQ scores compared to those with low AQ scores.

<Insert Table 5 around here>

<Insert Figures 2, 3 and 4 around here>

The results of the model with the SRS are summarized in Table 6. They confirm the main effects of Step and Condition as well as the interactions between Age and Step, and Age and Condition. However, the SRS only shows a trend toward significance as a main effect, and has no significant interaction with Condition. This model was not significantly different from a model without the SRS as a factor ($\chi^2 = 8.32$, $df = 8$, n.s.). Thus, there is no evidence that differences in the SRS have an impact on the effects of Continuum Type.

<Insert Table 6 around here>

Turning back to the AQ effects, we further explored the relationship between children's responses in the identification task and their scores in the AQ subscales (i.e., *social skills*, *attention switching*, *attention to detail*, *communication* and *imagination*). As our goal here was to understand the relative importance of these factors in predicting the response pattern and because the high degree of collinearity between the subscales rendered regression analyses unsuitable, we conducted binary recursive partitioning of the data using a Classification and Regression Tree (CART) analysis (Breiman, Friedman, Olshen, & Stone, 1984). We used the *rpart* function of R and grew a classification tree with the response pattern (/g/ or /k/) as the dependent variable and the five AQ subscale scores, Condition, Step, and Age as the predictor variables. Cost-complexity pruning was carried out using 10-fold cross-validation and by setting the complexity parameter at 0.013, which was the highest value that produced error scores within one standard error above the mean.

The resulting tree is shown in Figure 5. Each branching node partitions the data into two groups based on the specific decision rule. At the root node, the tree asks whether the stimulus comes from a step higher than 4.5 (in other words, Steps 5, 6, or 7). If the answer to this question is 'yes', the left branch is to be followed, where the next node asks whether the stimulus comes from a nonword-to-word continuum. Again, if 'yes', the left branch is to be followed, where the terminal node indicates '0' (i.e., /k/). This prediction is supported by 584 cases and contradicted by 406. The height of the nodes indicates the relative importance of the predictor. As can be seen from this, *attention to detail* and *attention switching* are the only subscores that figure in this analysis. First, the branch on the right half of the tree shows that children below the age of 5 years were more likely to give a /g/ response to stimuli with short VOTs (Steps 1–4), particularly if their *attention to detail* score was high. Second, the left side of the tree shows that the effect of Condition (i.e., the Ganong effect) interacted with both *attention switching* and *attention to detail*. For stimuli with long VOTs coming from word-to-nonword continua (e.g., *gift-kift*), children were generally more likely to respond /g/ compared to stimuli from nonword-to-word continua (e.g., *giss-kiss*), but this tendency was weaker if the *attention switching* score was high, especially if the *attention to detail* was low. The analysis here shows that the attenuation of the Ganong effect was associated primarily with high *attention switching* scores (i.e., difficulties in switching attention), and for those with high *attention switching* scores, also with low *attention to detail* scores.

<Insert Figure 5 around here>

Discussion

The main purpose of the current study was to investigate whether the influence of lexical information on the speech perception of children without ASC is related to variation in the AQ. We tested 4- to 7-year-olds' phoneme identification in VOT continua with lexical biases and analyzed the extent to which the identification function shifted across lexically different continua depending on their AQ scores. The results showed that the amount of identification shift can indeed be predicted by the AQ, such that children with higher AQ scores tended to be less affected by the lexical context of the auditory stimuli. This relationship was found independent of the age-related increase in the children's phoneme identification level and the concurrent developmental increase in their sensitivity to the acoustic difference along the VOT continua. It was not attributable to differences in sex or lexical knowledge (as measured in terms of lexical decision accuracy and latency) either.

The overall lexical effect found in the phoneme identification in 4- to 7-year-olds in our study is consistent with similar findings by Walley and Flege (1999) in 5-year-olds and 9-year-olds, a result that indicates that by the age of 4 or 5, children's speech perception involves integration of lexical information. A caveat here is the high proportion (23%) of children who were tested but not included in the analysis due to their failure in passing the fidelity test. This exclusion rate is comparable to that of the 5-year-olds tested in Walley & Flege (1999), 26% of whom produced data unsuitable for analysis, and demonstrates the difficulty that children of this age find in following the instructions for a phoneme identification task. Nevertheless, those who showed evidence of understanding the task exhibited a Ganong effect akin to that found in adults. In addition, our data offer evidence of a developmental change in the lexical effect (as shown by the interaction between age and continuum type) as well as the sensitivity to the VOT difference in the continua (as shown by the interaction between age and step on the response pattern). In this respect, the current study differs from Walley & Flege (1999), whose phoneme identification data for vowels did not show any difference in the size of the Ganong effect between 5-year-olds and 9-year-olds. This inconsistency may be due to differences between the perception of vowels (Walley & Flege, 1999) versus consonants (this study), but could also reflect differences in the lexical items in the experiments; the use of an early-acquired word (*bib*) in Walley and Flege's study may have suppressed potential effects deriving from age-related differences in lexical access.

The main findings related to the AQ in this study are largely comparable to the results from adults without ASC in Stewart and Ota (2008). In that study, the lexical effect was indexed to the mean difference in the proportion of voiced consonant response for each participant (the 'lexical identification shift' index, or LIS), which showed a negative correlation with the overall AQ score ($r_s = -.30$). The same analytical method applied to the current data with children yields a similar correlation between the LIS and total AQ ($r_s = -.32$, $N = 62$, $p < .05$). Furthermore, an even higher correlation between the LIS and the *attention switching* subscale could be found in both the adult data ($r_s = -.36$) and the child data ($r_s = -.37$, $N = 62$, $p < .05$). Together with the outcomes of the more controlled mixed-effects and CART analyses of the current study, these results confirm the robustness of the association between the AQ and the lexical effects on speech perception across age groups, and the primary role of the variance indexed to the *attention switching* subscale.

In this study, we also explored the possibility that the AQ effect in speech perception intrinsically reflects individual variance in autistic traits in the general population. However, our results showed limited support for this idea. First, the lexical identification shift in phoneme identification was not related to scores in the SRS. The SRS has a general focus on social behaviors associated with ASC and should also have covaried with the lexical identification differences if the source of the variance were associated with ASC. Second, the AQ subscales found to be related to the lexical effect in phoneme identification were mainly *attention switching* and, to some extent, *attention to detail*, those factors that are typically associated with a more general dimension of cognitive processing style than ASC. While it is true that difficulties in attention switching are reported for individuals with ASC, they are not part of the diagnostic criteria for clinical assessment of the condition (Kloosterman et al., 2011). Nor are difficulties in attention switching a unique characteristic of the population as they are also associated with people with ADHD or SLI (Cepeda, Cepeda, & Kramer, 2000; Kramer, Cepeda, & Cepeda, 2001; Marton & Schwartz, 2003). We also note in passing that recent clinical approaches to ASC (for example, those underlie DSM-V) tend to place more emphasis on social interaction and communication as diagnostic criteria, and less on aspects related to language and cognition, a trend that is consonant with the view that cognitive dimensions directly linked to language functioning are only tenuously related to ASC (see also Kjelgaard & Tager-Flusberg, 2001 for a theoretical discussion of this issue).

If the *attention switching* subscale is primarily responsible for the AQ-related variation in the phoneme identification task, in what way could it be related to the lexically-induced identification shift? Here, we appeal to the research outcomes on the role of attention in phoneme monitoring (e.g., Cutler, Mehler, Norris, & Segui,1987; Segui & Frauenfelder, 1986). Phoneme identification or monitoring tasks involve two processes: listening to speech (which usually lends itself to lexical access) and target detection (which is optimized by focusing on prelexical representation; that is, the acoustic signal). According to Cutler et al. (1987), listeners shift their attention between the lexical and prelexical codes as a function of the task. Phoneme monitoring can be performed optimally by attending primarily to prelexical information if the stimuli are invariant and repetitive (e.g., a set of monosyllables that only differ by the onset VOT). But some variation in the speech dimension, such as the use of multiple real words, will also draw the listener's attention to lexical information. Thus the degree to which listeners exhibit a lexical identification shift in the type of task we employed depends on how much they perseverate on prelexical processing in the face of variability in the lexical information. It is this aspect of cognitive processing that may be measured by the *attention switching* items in the AQ (e.g., "S/he frequently gets so strongly absorbed in one thing that s/he loses sight of other things", "If there is an interruption, s/he can switch back to what s/he was doing very quickly").

In conclusion, this study demonstrates that AQ scores predict the level of lexical effect on speech perception in children without ASC, augmenting previous findings from adults. The results were primarily related to the attention switching component of the AQ but not to the SRS, indicating that the source of this variance is likely to be a general dimension of cognitive processing style, possibly related to the integration and/or switching between local and global information, rather than cognitive mechanisms underlying ASC. Such an interpretation aligns with previous findings of AQ-related variation in adults in speech processing tasks (e.g., Stewart & Ota, 2009; Yu, 2010; Yu et al., 2013), as well as in other types of tasks that involve dual-level information processing (e.g., Clark et al., 2013; Stewart et al., 2009). While these findings are intriguing, we still do not fully understand why an instrument originally designed to test traits associated with ASC also captures individual differences in a range of cognitive tasks across domains. An important task for future work is to zero in on the nature of the underlying individual variance by triangulating the AQ-based results with measures of other cognitive dimensions, such as selective attention, suppression and working memory. Among other things, such investigations will tell us whether the observed AQ effects are better understood as the combined workings of already known nonsensory factors or as a manifestation of a new dimension of cognitive processing.

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References

Almeida, R., Dickinson, J. E., Maybery, M., Badcock, J., & Badcock, D. (2009). A new step towards understanding embedded figures test performance in the autism spectrum. *Journal of Vision, 9*, 1204-1204.

Armstrong, K., & Iarocci, G. (2013). Brief Report: The Autism-Spectrum Quotient has convergent validity with the Social Responsiveness Scale in a high-functioning sample. *Journal of Autism and Developmental Disorders, 43*, 2228-2232.

Austin, E. J. (2005). Personality correlates of the broader autism phenotype as assessed by the Autism-Spectrum Quotient (AQ). *Personality and Individual Differences, 38*, 451–460.

Auyeung, B., Baron-Cohen, S., Wheelwright, S., & Allison, C. (2008). The Autism-Spectrum quotient: Children's version (AQ-Child). *Journal of Autism and Developmental Disorders, 38,* 1230-1240.

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): Evidence from Asperger syndrome/high-functioning autism, males, females, scientists and mathematicians. *Journal of Autism & Developmental Disorders, 31*, 5–17.

BNC Consortium (2007). *The British National Corpus*, version 3 (BNC XML Edition). Distributed by Oxford University Computing Services.

Bonnel, A., Mottron, L., Peretz, I., Trudel, M., & Gallun, E. (2003). Enhanced pitch sensitivity in individuals with autism: A signal detection analysis. *Journal of Cognitive Neuroscience, 15*, 226-235.

Breiman, L., Friedman, J. H., Olshen, R. A., & Stone, C. J. (1984). *Classification and regression trees.* Monterey, CA: Wadsworth & Brooks.

Cepeda, N. J., Cepeda, M. L., & Kramer, A. F. (2000). Task switching and attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology, 28,* 213-226.

Chynn, E. W., Garrod, A., Demick, J., & DeVos, E. (1991). Correlations among field dependence-independence, sex-role stereotype, and age of preschoolers. *Perceptual and Motor Skills, 73*, 747-756.

Clark, A. I., Hughes, P. S., Grube, M., & Stewart, M. E. (2013). Autistic traits and sensitivity to interference with flavour identification. *Autism Research, 6*, 332-336.

Constantino, J. N., & Gruber, C. P. (2005). *The Social Responsiveness Scale Manual*. Los Angeles, CA: Western Psychological Services.

Constantino, J. N., & Todd, R. D. (2003). Autistic traits in the general population: A twin study. *Archives of General Psychiatry, 60,* 524-530.

Cutler, A., Mehler, J., Norris, D., & Segui, J. (1987). Phoneme identification and the lexicon. *Cognitive Psychology, 19,* 141-177.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin & Review, 3(4),* 422-433.

Francis, A. L., & Nusbaum, H. C. (2002). Selective attention and the acquisition of new phonetic categories. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 349.

Frankish, C. (2008). Precategorical acoustic storage and the perception of speech. *Journal of Memory and Language, 58*, 815-836.

Frith, U. (1989). *Autism: Explaining the enigma*. Oxford: Blackwell.

Frith, U., & Happé, F. (1994). Autism: Beyond "theory of mind". Cognition, 50, 115-132.

Gernsbacher, M. A. (1997). Two decades of structure building. *Discourse Processes, 23*, 265-304.

Haesen, B., Boets, B., & Wagemans, J. (2011). A review of behavioural and electrophysiological studies on auditory processing and speech perception in autism spectrum disorders. *Research in Autism Spectrum Disorders, 5*, 701-714.

Happé, F. (1996). Studying weak central coherence at low levels: Children with autism do not succumb to visual illusions: A research note. *Journal of Child Psychology & Psychiatry & Allied Disciplines, 37*, 873–877.

Happé, F., & Frith, U. (2006). The weak coherence account: Detail-focused cognitive style in autism spectrum disorders. *Journal of Autism & Developmental Disorders*, 36, 5–25.

Heaton, P. (2003). Pitch memory, labelling and disembedding in autism. *Journal of Child Psychology and Psychiatry, 44*, 543-551.

Heaton, P., Hudry, K., Ludlow, A., & Hill, E. (2008). Superior discrimination of speech pitch and its relationship to verbal ability in autism spectrum disorders. *Cognitive Neuropsychology, 25*, 771-782.

Hoekstra, R. A., Bartels, M., Verweij, C. J. H., & Boomsma, D. I. (2007). Heritability of autistic traits in the general population. *Archives of Pediatrics & Adolescent Medicine, 161*, 372–377.

Holt, L. L., & Lotto, A. J. (2010). Speech perception as categorization. *Attention, Perception, & Psychophysics, 72*, 1218-1227.

Hurst, R. M., Nelson-Gray, R. O., Mitchell, J. T., & Kwapil, T. R. (2007). The relationship of Asperger's characteristics and schizotypal personality traits in a non-clinical adult sample. *Journal of Autism and Developmental Disorders, 37*, 1711–1720.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*, 122-149.

Kjelgaard, M. M., & Tager-Flusberg, H. (2001). An investigation of language impairment in autism: Implications for genetic subgroups. *Language and Cognitive Processes, 16*, 287-308.

Kloosterman, P. H., Keefer, K. V., Kelley, E. A., Summerfeldt, L. J., & Parker, J. D. (2011). Evaluation of the factor structure of the Autism-Spectrum Quotient. *Personality and Individual Differences, 50,* 310-314.

Kramer, A. F., Cepeda, N. J., & Cepeda, M. L. (2001). Methylphenidate effects on task-switching performance in attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 40*, 1277-1284.

Kuperman, V., Stadthagen-Gonzalez, H., & Brysbaert, M. (2012). Age-of-acquisition ratings for 30,000 English words. *Behavior Research Methods, 44,* 978-990.

Marton, K., & Schwartz, R. G. (2003). Working memory capacity and language processes in children with specific language impairment. *Journal of Speech, Language and Hearing Research, 46,* 1138.

Mottron, L., & Burack, J. A. (2001). Enhanced perceptual functioning in the development of autism. In J. A. Burack, T. Charman, N. Yirmiya, & P. R. Zelazo (Eds). *The development of autism: Perspectives from theory and research*, (pp. 131-148). Mahwah, NJ: Lawrence Erlbaum.

Mottron, L., Dawson, M., Soulieres, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: an update, and eight principles of autistic perception. *Journal of Autism and Developmental Disorders, 36*, 27-43.

R Development Core Team (2011). *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing.

Segui, J., & Frauenfelder, U. (1986). The effect of lexical constraints on speech perception. In F. Klix & H. Hagendorf (Eds.), *Human memory and cognitive abilities: Symposium in memoriam of Hermann Ebbinghaus* (pp. 795–808). Amsterdam: North-Holland.

Stewart, M. E., & Austin, E. J. (2009). The structure of the Autism-Spectrum Quotient (AQ): Evidence from a student sample in Scotland. *Personality and Individual Differences, 47*, 224-228.

Stewart, M. E., & Ota, M. (2008). Lexical effects on speech perception in individuals with "autistic" traits. *Cognition, 109,* 157-162.

Stewart, M. E., Watson, J., Allcock, A. J., & Yaqoob, T. (2009). Autistic traits predict performance on the block design. *Autism, 13*, 133-142.

Stoecker, J. J., Colombo, J., Frick, J. E., & Allen, J. R. (1998). Long-and short-looking infants' recognition of symmetrical and asymmetrical forms. *Journal of Experimental Child Psychology, 71*, 63-78.

Tipper, S. P., & Baylis, G. C. (1987). Individual differences in selective attention: The relation of priming and interference to cognitive failure. *Personality and Individual Differences, 8*, 667-675.

Wainer, A. L., Ingersoll, B. R., & Hopwood, C. J. (2011). The structure and nature of the broader autism phenotype in a non-clinical sample. *Journal of Psychopathology and Behavioral Assessment, 33*, 459-469.

Walley, A. C., & Flege, J. E. (1999). Effect of lexical status on children's and adults' perception of native and non-native vowels. *Journal of Phonetics, 27,* 307-332.

Watson, C. S., Qui, W. W., Chamberlain, M. M., Li, X. (1996). Auditory and visual speech perception: Confirmation of a modality independent source of individual differences. *Journal of the Acoustical Society of America, 100*, 1153–1162.

Witkin, H. A., Dyk, R. B., Fattuson, H. F., Goodenough, D. R., & Karp, S. A. (1962). *Psychological differentiation: Studies of development*. Oxford: Wiley.

Witkin, H. A., & Goodenough, D. R. (1981). *Cognitive styles, essence and origins: Field dependence and field independence*. New York: International Universities Press.

Yu, A. C. L. (2010). Perceptual compensation is correlated with individuals' "autistic" traits: Implications for models of sound change. *PloS one, 5,* e11950.

Yu, A. C. L, Abrego-Collier, C., & Sonderegger, M. (2013) Phonetic imitation from an individual-difference perspective: Subjective attitude, personality and "autistic" traits. *PLoS ONE 8*, e74746.

Table 1

Voice onset time (ms) of auditory stimuli used in the phoneme identification task

	Step						
Continuum pair	1	2	3	4	5	6	7
gift-kift *giss-kiss*	25.5	32.6	40.8	49.3	55.5	64.0	76.6
geese-keese *geep-keep*	23.6	30.0	36.9	47.7	57.0	66.1	77.1
guess-kess *gept-kept*	19.6	28.1	36.2	44.8	52.6	60.8	69.4

Table 2

Descriptive statistics of measured variables

Factor	Mean	Range	SD
AQ	37.6	5-69	16.4
SRS	23.6	0-77	16.6
Auditory discrimination (%)	71.2	32-94	15.5
Lexical decision (RT in ms)	2330	1086-12180	1544

Table 3

Correlations between main independent factors

	SRS	Age	Discrimination	Lexical decision
AQ total	.696**	.113	-.037	.122
SRS total		.249	-.024	-.003
Age (months)			.145	-.401**
Discrimination				-.226

Note: '**' $p < .01$

Table 4
Correlations between AQ and SRS subscales

	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
AQ subscales									
(1) Social skills	$.61^{**}$	-.02	$.68^{**}$	$.64^{**}$	$.36^{*}$	$.66^{**}$	$.65^{**}$	$.60^{**}$	$.57^{**}$
(2) Attention switching		.12	$.61^{**}$	$.56^{**}$	$.31^{*}$	$.50^{**}$	$.55^{**}$	$.48^{**}$	$.61^{**}$
(3) Attention to detail			.17	.14	.12	$.27^{*}$	$.30^{*}$	.22	$.44^{**}$
(4) Communication				$.53^{**}$	$.40^{**}$	$.68^{**}$	$.70^{**}$	$.44^{**}$	$.57^{**}$
(5) Imagination					.22	$.61^{**}$	$.66^{**}$	$.55^{**}$	$.56^{**}$
SRS subscales									
(6) Social awareness						$.64^{**}$	$.62^{**}$	$.53^{**}$	$.53^{**}$
(7) Social info processing							$.82^{**}$	$.66^{**}$	$.70^{**}$
(8) Social responses								$.65^{**}$	$.75^{**}$
(9) Social anxiety/avoidance									$.57^{**}$
(10) Preoccupations									

Note: '*' $p < .05$, '**' $p < .01$

Table 5

Predictor estimates (with the AQ) for responses in the identification task

	β	SE(β)	z	p
Intercept	0.661	0.147	4.509	< .001***
Condition	-1.341	0.142	-9.462	< .001***
Step	-0.480	0.022	-21.882	< .001***
AQ	-0.002	0.009	-0.191	.848
Age (days)	-0.145	0.338	-0.429	.668
Condition × Step	-0.047	0.043	-1.094	.274
Condition × AQ	0.024	0.009	2.693	.007**
Step × AQ	0.002	0.001	1.618	.106
Condition × Age	-1.058	0.326	-3.242	.001**
Step × Age	-0.270	0.051	-5.336	< .001***
AQ × Age	0.003	0.019	-0.153	.879
Condition × Step × AQ	0.000	0.003	0.075	.940
Condition × Step × Age	0.012	0.099	0.121	.903
Condition × AQ × Age	0.016	0.018	0.886	.376
Step × AQ × Age	0.004	0.003	1.633	.102
Condition × Step × AQ × Age	-0.005	0.005	-0.957	.339

Note: '**' $p < .01$, '***' $p < .001$

Table 6

Predictor estimates (with the SRS) for responses in the identification task

	β	SE(β)	z	p
Intercept	0.666	0.144	4.643	< .001***
Condition	-1.340	0.150	-8.954	< .001***
Step	-0.481	0.022	-21.651	< .001***
SRS	-0.032	0.017	-1.822	.068
Age (days)	-0.048	0.334	-0.145	.885
Condition × Step	-0.054	0.043	-1.255	.210
Condition × SRS	0.027	0.018	1.508	.132
Step × SRS	0.002	0.003	0.809	.419
Condition × Age	-1.030	0.344	-2.991	.002**
Step × Age	-0.259	0.051	-5.120	< .001***
SRS × Age	-0.004	0.040	-0.115	.909
Condition × Step × SRS	0.001	0.005	0.203	.839
Condition × Step × Age	-0.005	0.099	-0.053	.958
Condition × SRS × Age	0.003	0.042	0.080	.937
Step × SRS × Age	0.006	0.006	1.121	.262
Condition × Step × SRS × Age	0.005	0.012	0.490	.624

Note: '**' $p < .01$, '***' $p < .001$

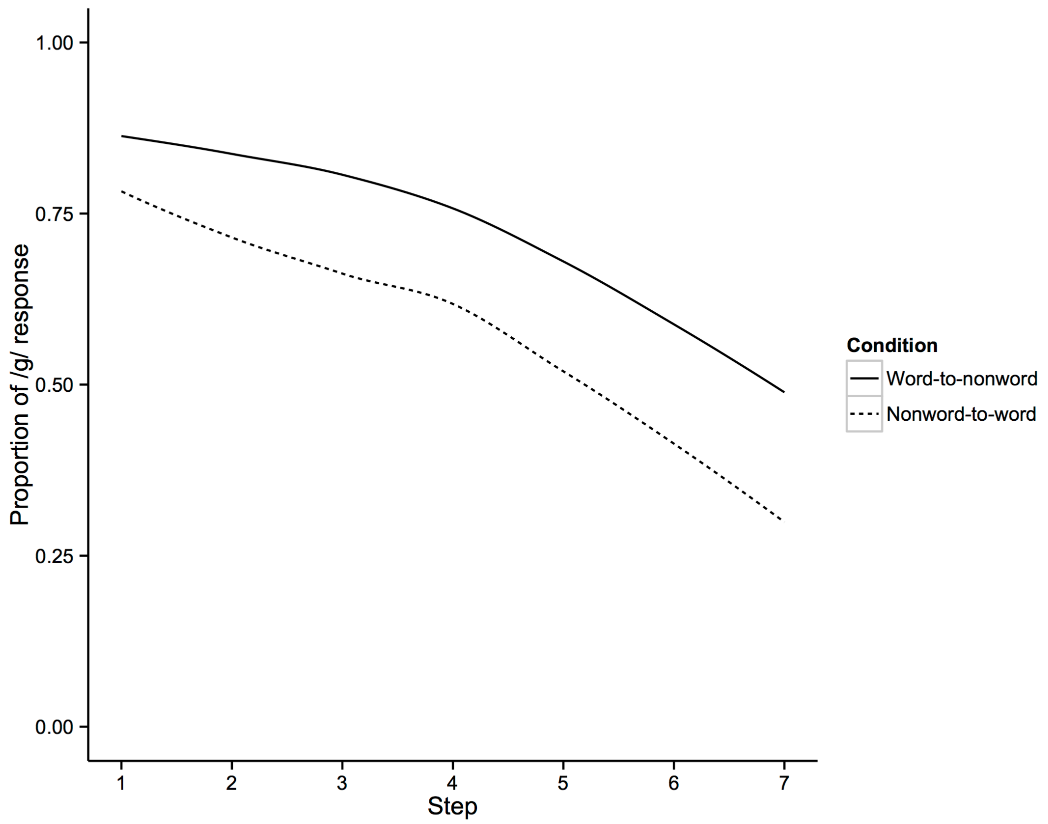


Figure 1. Proportion of /g/ responses in the phoneme identification task. The x-axis represents steps in VOT from the shortest ('1') to the longest ('7'). Real-to-nonword continua had a real word on the lower VOT end (e.g., *gift-kift*); Nonword-to-real continua had a nonword on the lower VOT end (e.g., *giss-kiss*).

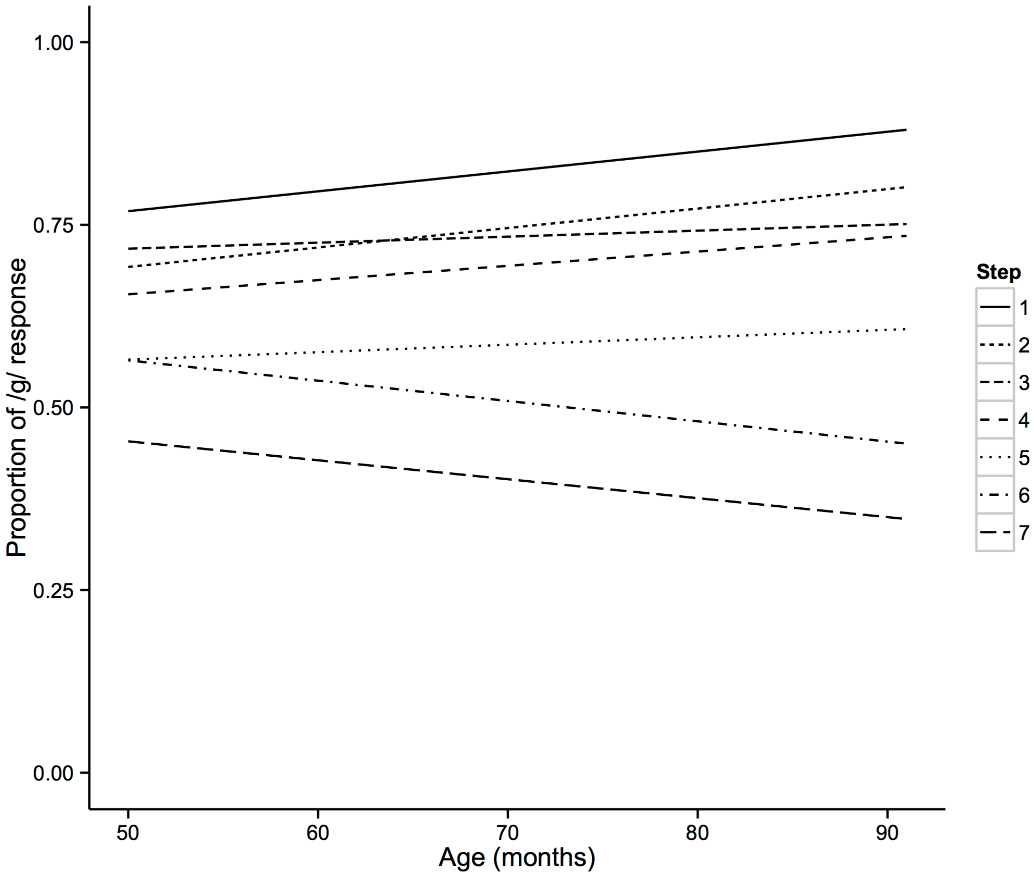


Figure 2. Interaction between age and step. Values for step are backtransformed to the original scale and age is shown in months.

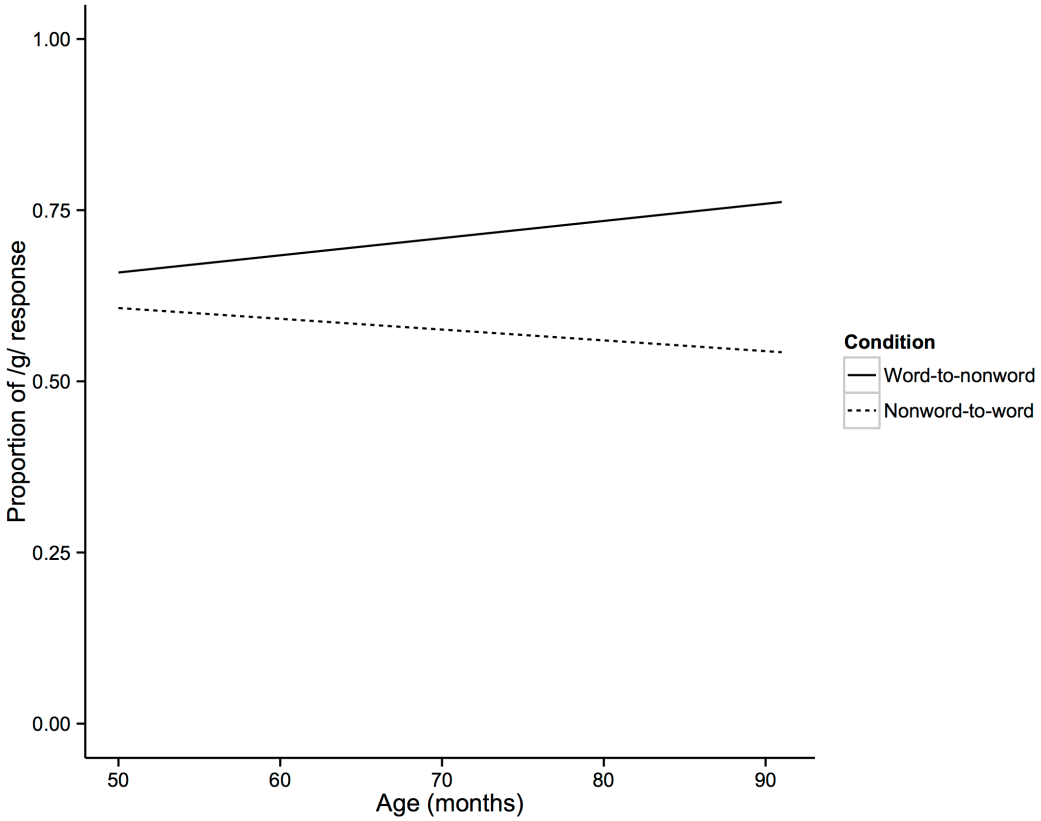


Figure 3. Interaction between age and condition. Age is shown in months.

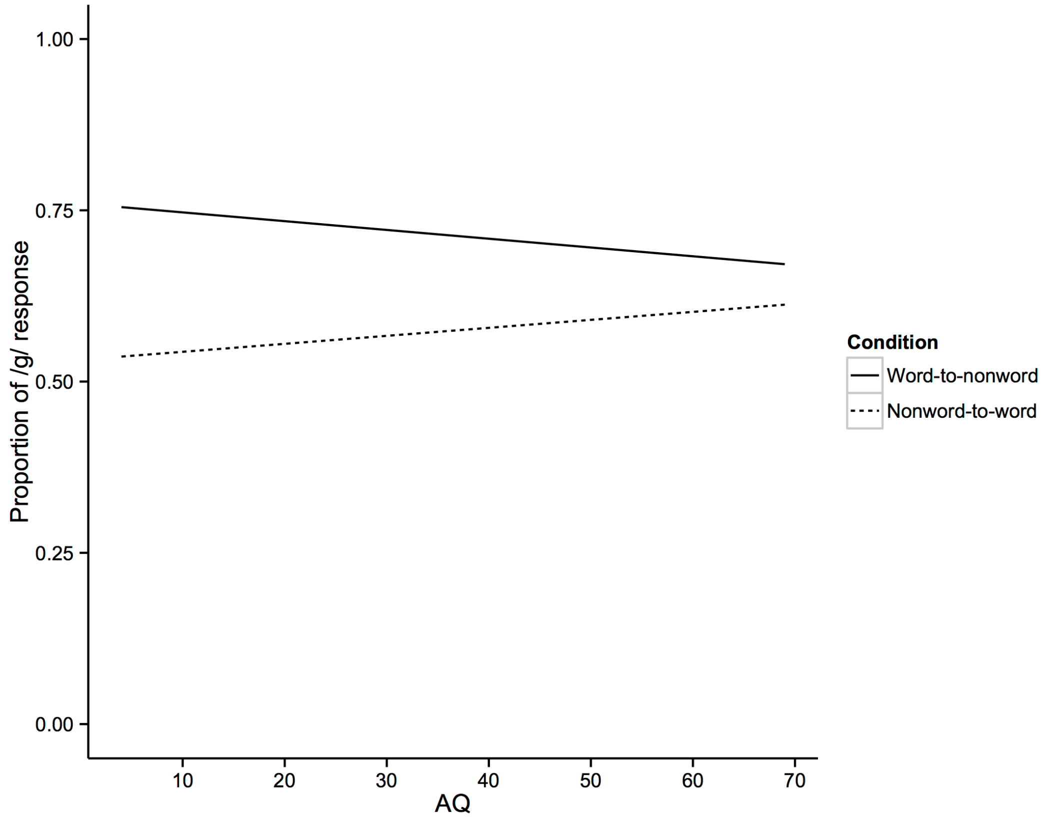


Figure 4. Interaction between AQ and condition. Values for AQ are backtransformed to the original scale.

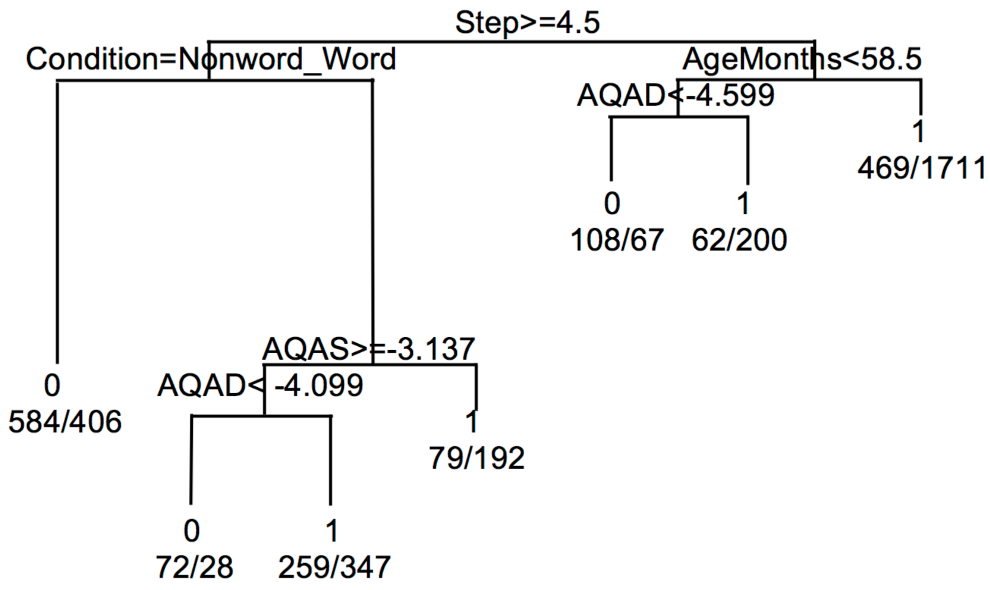
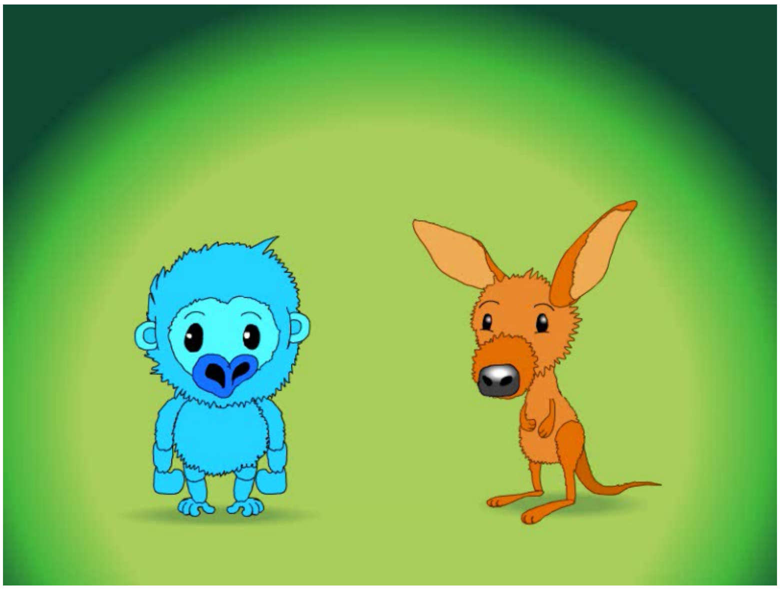


Figure 5. CART tree for the response pattern (0 = /k/, 1 = /g/) in the identification task. Age is shown in months. AQAS = *attention switching* in the AQ. AQAD = *attention to detail* in the AQ.

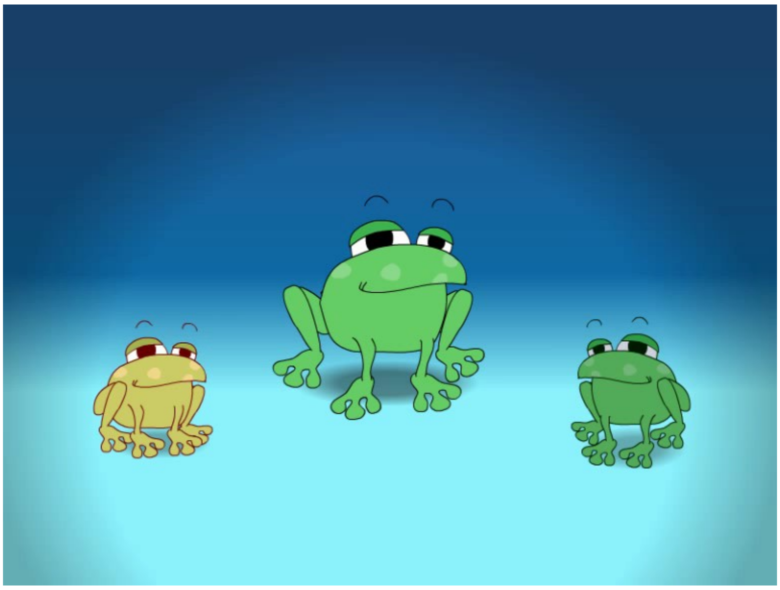
Supplementary Materials

Experimental items used in the lexical decision task

Contrast	Real word	Nonword
b/p	*bag*	*pag*
b/p	*boat*	*poat*
b/p	*pink*	*bink*
b/p	*point*	*boint*
t/d	*deep*	*teep*
t/d	*desk*	*tesk*
t/d	*take*	*dake*
t/d	*tooth*	*dooth*
k/g	*get*	*ket*
k/g	*guy*	*kuy*
k/g	*count*	*gount*
k/g	*cake*	*gake*



Screen shot of the two animated characters used in the phoneme identification task.



Screen shot of animation used in the nonword XAB discrimination task. The large frog 'croaked' the X item, and the two small frogs 'croaked' the A and B items.