



Neural Processing of Speech Sounds in Autistic Kindergarteners as a Predictor of Reading Outcomes

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Abstract

Phonology is an important foundation of reading development; however, little is known about the neural substrates of speech sound processing and reading development in autistic children. We investigated early auditory event-related potentials (ERPs) in response to speech sounds and their association with reading ability (word recognition and reading comprehension). 56 kindergarteners (28 ASD, 28 TD) completed an ERP task using rhyming, bisyllabic pseudowords (/gibu/ and /bidu/) in an old/new design: 50% “old” and 50% “new” stimuli presented following a sensitization block of 100% “old” stimuli. Behavioral measures of reading ability were completed at kindergarten entry and exit. Results from generalized linear mixed models revealed a significant three-way interaction between stimuli (“new” vs. “old”), diagnosis (ASD vs. TD), and reading ability (for word recognition and reading comprehension) for P1 and P2 amplitude. Follow-up analyses revealed that autistic children with lower reading abilities showed greater P1 and P2 amplitudes for “new” vs. “old” stimuli, with effects ranging from marginal to significant (p 's 0.04–0.07). Regression analyses revealed that old/new ERP difference scores significantly predicted later word recognition at kindergarten year-end (P1 amplitude: $p = .05$; P2 amplitude: $p = .04$), but not reading comprehension, controlling for sex and nonverbal IQ. Autistic children with poorer reading skills, specifically those with weaker word recognition abilities, show neural differences when processing speech sounds compared to autistic peers with greater reading ability and typically developing children. A better understanding of the neural basis of speech sound processing could enhance our insight into the heterogeneity in reading among individuals with ASD and guide future treatment approaches.

Keywords Phonology · Speech sound processing · Autism · Reading · ERPs · Child language development

With improvements in the accessibility and quality of early interventions services, a greater number of children with autism spectrum disorder (ASD) are participating in general education and inclusive classrooms with their typically developing (TD) peers (Bolourian et al., 2020). In 2019,

approximately two thirds of students with developmental delays spent most of their day in a general education classroom (National Center for Education Statistics, 2022). While these findings are encouraging, we still have much to learn about which factors contribute to the academic success of autistic children.¹ Many autistic children make academic progress commensurate with or higher than their cognitive ability; however, academic abilities in a substantial subgroup of autistic children are still more delayed than what would be expected given their intellectual ability (Estes et al., 2011; Kim et al., 2018). Approximately one quarter to one third of autistic children who have within average intellectual skills demonstrate academic delays (Kim et al., 2018), and it can be difficult to predict which children will make academic gains with typical classroom instruction and which will require more targeted academic support.

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¹ Throughout this manuscript we use the term “autistic children” to best reflect the identity of many in autistic community (Bury et al., 2023).

Word Recognition and Reading Comprehension in ASD

Academic skills are influenced by various factors including cognitive abilities, executive function, and social skills (Duncan et al., 2007; Mayes et al., 2009; McLeod et al., 2012), but one area of particular challenge for many autistic children is reading (Brown et al., 2013; Nation et al., 2006; Sorenson Duncan et al., 2021). There is significant heterogeneity in the individual reading abilities of autistic children (Westerveld et al., 2016). While some autistic children develop adequate reading skills or even excel in reading (Estes et al., 2011; Kim et al., 2018; Vale et al., 2022), many autistic children still struggle to learn to read (Davidson & Ellis Weismer, 2014; Huemer & Mann, 2010; Ostrolenk et al., 2017), with challenges in both reading comprehension (Davidson & Ellis Weismer, 2014; Huemer & Mann, 2010; Ostrolenk et al., 2017) and word recognition (Estes et al., 2011; Johnels et al., 2019; Nation et al., 2006; Sorenson Duncan et al., 2021). Reading comprehension challenges are well documented in children with ASD (Jones et al., 2009; Sorenson Duncan et al., 2021). This is not surprising as reading comprehension is correlated with both oral language skills and intellectual functioning (Knight et al., 2019), two additional areas of frequent weakness in ASD (Bacon et al., 2019; Bishop & Snowling, 2004; Tager-Flusberg et al., 2009). Consistent with the Simple View of Reading (Hoover & Gough, 1990), these language challenges appear to impact reading comprehension directly (Dolean et al., 2021; Gough & Tunmer, 1986). As the difficulty level of reading increases, basic oral language skills become especially critical for understanding texts (Bishop & Snowling, 2004).

Furthermore, word recognition challenges are also associated with poor reading outcomes in autistic children (Sorenson Duncan et al., 2021). Profiles of autistic children with strong word recognition but poor reading comprehension skills are frequently discussed; however, the number of autistic children with poor word recognition skills may outnumber those with “hyperlexic” profiles (i.e., children with high word recognition but poor reading comprehension skills; Johnels et al., 2019; Nation et al., 2006). In one study, over 25% of autistic children had word recognition skills significantly below what was expected for their cognitive age (Estes et al., 2011), and a recent meta-analysis found that word recognition and oral language skills contribute equally to reading comprehension in autistic children (Sorenson Duncan et al., 2021). Thus, to fully examine reading skills in children with ASD, researchers must consider impairments in both word recognition and reading comprehension.

Phonological Processing and Reading Outcomes in ASD

One foundational linguistic skill, phonological processing, or the “use of phonological information (i.e. the sounds of one’s language) in processing written and oral language” (Wagner & Torgesen, 1987, p. 1), supports the development of reading skills (Åsberg Johnels et al., 2019; Ehrhorn et al., 2021; Georgiou et al., 2008; Newman et al., 2007; Swanson et al., 2003). A large body of research has linked poor phonological processing, including phonological working memory and phonological awareness deficits, to reading skills (Bar-Kochva & Nevo, 2019; Boets et al., 2010; Hakvoort et al., 2016; Hogan et al., 2005; Hulme et al., 2012; Knoop-van Campen, 2018; Loucas et al., 2016; Smith et al., 2008; Snowling et al., 1986; Vellutino et al., 2004). Phonological abilities prior to and at the onset of learning to read are predictive of later reading ability (Melby-Lervåg et al., 2012) and this relation is present in both typically developing children (Georgiou et al., 2008; Swanson et al., 2003; Wagner et al., 1994) and those with reading disorders (Ehrhorn et al., 2021; Smith et al., 2008).

In addition to the clear link between phonological processing and reading in other disorders, there is evidence that phonological abilities are also impacted in autistic children (Åsberg Johnels et al., 2019; Dynia et al., 2017, 2019; Jokel et al., 2021; Newman et al., 2007), particularly in those with co-occurring language impairment (Whitehouse et al., 2008; Williams et al., 2013). In a sample of autistic children with higher intellectual functioning, more than half demonstrated impaired phonological skills; children’s nonword repetition skills were correlated with pre-reading skills (e.g. rapid automatized naming) and expressive language skills (Tager-Flusberg, 2006). In another study, autistic children showed difficulties with nonword repetition, which suggested a weakness in phonological working memory (Jokel et al., 2021). On the other hand, many autistic children, especially those with within-average oral language and reading skills, show similar phonological skills to typically developing peers with similar language ability (Harper-Hill et al., 2013). Thus, impairments in phonological processing, which one study showed were greatest in autistic children with both poor word recognition and poor reading comprehension skills (Åsberg Johnels et al., 2019), may help explain why some autistic children learn to read without difficulty and other display more pronounced challenges.

ERP Measures of Speech Sound Processing and Language Ability in ASD

Beyond behavioral measures, event-related potentials (ERPs), are neural responses recorded at the scalp to repeated, time-locked stimuli (Luck, 2014). These measures can be used to examine auditory processing skills that support linguistic tasks, including early time-scale speech sound processing challenges that may give rise to later spoken and written language challenges. The *Phonological Perceptual Deficit Theory* (Joanisse & Seidenberg, 2003) posits that language and reading challenges begin with deficits in speech sound processing. Degraded speech perception leads to poor phonological working memory, unstable linguistic representations, and impairments in language and reading development (Joanisse & Seidenberg, 2003). Longitudinal behavioral work has found an association between speech sound perception, including as early as infancy (Kuhl et al., 2005), and later reading skills (Kuhl et al., 2005; Spencer & Oleson, 2008).

ERP components reflecting early time-scale sensory processing are commonly studied in developmental literature (Silva et al., 2017). In auditory paradigms, early ERP components may index the encoding of acoustic features (e.g. P1 and P2 components; Key et al., 2005; Näätänen & Picton, 1987), reflect build-up of neural representations (e.g. N2 component; Karhu et al., 1997), and are sensitive to unexpected change in acoustic information (e.g. early MMN component; Baldeweg et al., 1999). These neural responses likely reflect encoding of speech information in addition to auditory features like tone and duration (Gu & Bi, 2020).

Differences in early neural responses to auditory stimuli, including speech and nonspeech sounds, are seen in children with a variety of developmental disorders, and are associated with both language and reading ability (Archibald & Joanisse, 2011; Bonte et al., 2007; Bishop, 2007; Bruder et al., 2011; Espy et al., 2004; Hämäläinen et al., 2013; Harwood et al., 2022; Kuhl, 2011; Malins et al., 2013; McWeeny & Norton, 2024; Rotschafer, 2021). Brain responses as early as infancy may be predictive of later, elementary reading skills (Leppänen et al., 2012). In addition to evidence in other populations, previous research has shown that autistic children may have auditory processing deficits including prolonged latencies of early neural responses (Matsuzaki et al., 2019; Rosenhall et al., 2003; Roth et al., 2012) suggesting delays in auditory processing, and decreased amplitude of several early ERP components (e.g. P1, N2, MMN) (Chen et al., 2020; Donkers et al., 2015; Guiraud et al., 2011; Hudac et al., 2018; Ruiz-Martínez et al., 2020; Russo et al., 2009). For example, differences in P1 responses to consonant–vowel (CV) stimuli were related to language skills in one group of autistic children (Russo et al., 2009).

Other studies have also investigated whether autistic children are sensitive to unexpected changes in sounds using an oddball paradigm like the MMN (Kasai et al., 2005; Key & Slaboch, 2021; Key et al., 2016; Ludlow et al., 2014), in which a deviant stimulus is played in a stream of standard stimuli. These paradigms may manipulate frequency, intensity, or duration of nonspeech sounds to examine auditory processing abilities or alter speech sound stimuli directly to examine speech sound processing. In one study, reduced brain responses to speech-sound deviants were related to language impairments in a group of autistic children (Key et al., 2016). Results, however, have been inconsistent across studies (Chen et al., 2020; Key & Slaboch, 2021; Schwartz et al., 2018). One meta-analysis found weaker MMN responses to nonspeech sounds in ASD, reflecting difficulty processing complex tones, but not to speech sounds (Schwartz et al., 2018), while another reported significant amplitude and latency differences to speech-sound deviants (Chen et al., 2020). Conversely, some studies have found that enhancement of neural activity during auditory discrimination tasks rather than suppression is associated with impairments in language ability (Lepisto et al., 2007; Matsuzaki et al., 2019).

Finally, another group of work has used an old/new ERP design to examine neural responses to “new” (unlearned) vs. “old” (learned) novel speech sounds (Molfese, 2000; Molfese & Molfese, 1985, 1997). In these studies, ERP responses to “new” vs. “old” stimuli were related to school-age reading ability (Molfese, 2000) and oral language skills (Molfese & Molfese, 1997) in children followed from infancy to age 8. Specifically, children with dyslexia and “poor readers” with a below average IQ score, showed a poorly formed N1 component with delayed latency in infancy compared to typical readers (Molfese & Molfese, 1997). More recent work by Harwood and colleagues using this paradigm in a non-clinical sample of toddlers with varying language ability has shown that children with better language skills had faster ERP responses to the novel pseudowords (Harwood et al., 2017), greater positivity of the P1 component for “new” stimuli compared to “old” stimuli, and less negativity of the N2 component for “new” stimuli compared to “old” stimuli (Harwood et al., 2022). Despite this paradigm’s application in a variety of language and reading disorders, it has yet to be used in work with ASD populations.

ERP Measures of Speech Sound Processing and Reading Achievement in ASD

Across ERP studies of speech sound processing, mixed results suggest that the patterns of neural responses may vary widely depending on the population and developmental levels of the samples as well as methodologies and paradigms

used to obtain brain responses. Furthermore, whereas ERPs have been used to characterize broader auditory processing deficits and speech sound processing in autistic populations (Chen et al., 2020; Donkers et al., 2015; Guiraud et al., 2011; Hudac et al., 2018; Ruiz-Martínez et al. 2020; Russo et al., 2009; Schwartz et al., 2018), including more specific relations with oral language ability (Matsuzaki et al., 2019; Russo et al., 2009), and language and reading development in other populations (Harwood et al., 2017, 2022; Leppänen et al., 2012), limited work has examined neural processing of speech sounds and its relation to reading impairments in children with ASD. Given behavioral work showing that autistic children exhibit impaired phonological processing (Åsberg Johnels et al., 2019; Jokel et al., 2021; Newman et al., 2007) and reading skills (Brown et al., 2013; Davidson & Ellis Weismer, 2014; Huemer & Mann, 2010; Nation et al., 2006), understanding the neural underpinning of these weaknesses is an important next step. Furthermore, examining such relations before and after a year of kindergarten reading instruction could ultimately inform intervention approaches for autistic children with phonological weaknesses and identify which children are in most need of early, targeted academic support.

Current Study

Thus, in the current study, we examined early neural processing of speech sounds in kindergarteners with ASD and the relation to word recognition and reading comprehension, both concurrently and across the kindergarten year, a key period of academic development. We used rhyming, bisyllabic, pseudowords (/gibu/and/bidu/) in an old/new design: 50% “old” and 50% “new” stimuli presented following a sensitization block of 100% “old” stimuli (Harwood et al., 2017, 2022; Landi et al., 2012), originally modeled on the work of Molfese and colleagues (Molfese & Molfese, 1985). We here extended this research to focus on kindergarteners with ASD, as very little is known about the neural processing of speech sounds in this population during the developmentally critical period in which children are starting formal education.

We focused on the P1-P2-N2 complex in fronto-central electrodes (see ERP selection in Methods), which reflect encoding of acoustic features of auditory stimuli during passive tasks as well as stimulus detection and classification (Key et al., 2005; Silva et al., 2017). Previous work with this paradigm has shown that these neural components reflect phonemic sensitivity and are related to differences in linguistic ability (Harwood et al., 2022). In typical development, the P1 is visible around 100 ms in toddlers followed by a negative N2 peak around 200 ms. The P1 component decreases in latency with age, nearing 50 ms by

later elementary school, as well as a gradual reduction in the latency of the N2 component (Gilley et al., 2005; Sharma et al., 1997; Silva et al., 2017). In some studies, a P2 component is visible, possibly from bifurcation of the P1 component that reflects maturation of the central nervous system (Silva et al., 2017). P1-P2-N2 components have been used to investigate phonological processing in children with reading and language delays/disorders (Harwood et al., 2022; McArthur et al., 2009) and may be attenuated in samples of autistic children compared to typically developing peers (Donkers et al., 2015).

We hypothesized that: (1) at kindergarten entry, autistic children would differ in neural processing of “new” vs. “old” phonemic stimuli compared to typically developing children; (2) neural processing of speech sounds would be related to reading skills (word recognition and reading comprehension skills) such that autistic children with better reading skills would show increased P1/P2 amplitude for “new” compared to “old” phonemic stimuli; (3) in children with ASD, neural processing of speech sounds would predict word recognition and reading comprehension skills at kindergarten end. To test these hypotheses, we examined whether there were diagnostic group differences in amplitudes of ERP components related to speech sound processing at kindergarten entry and whether the amplitudes were related to concurrent word recognition and reading comprehension skills. We also examined whether old/new ERP difference scores were predictive of future reading skills in autistic children at the end of kindergarten. Finally, we mainly focused on the P1 and P2 components for analyses as these are prominent in children this age (Sharma et al., 1997; Silva et al., 2017); however, we also explored whether we would see the same patterns for the N2 component, which is related to speech sound processing in younger children (Gilley et al., 2005; Harwood et al., 2022; Sharma et al., 1997; Silva et al., 2017). These are reported in the supplemental materials.

Methods

Participants

Participants were recruited as part of a larger, longitudinal study examining brain and behavioral predictors of kindergarten achievement designed to examine academic outcomes in verbal children with ASD that have average to above-average cognitive abilities (a full description of participant recruitment was previously reported here (Buzzell et al., 2022)). Therefore, inclusion criteria were no intellectual disability, parent-reported use of complex sentences at kindergarten entry, and English as the primary language spoken. All children had a previous diagnosis of ASD, which was further confirmed using the gold standard behavioral

assessment, the Autism Diagnostic Observation Schedule-2, Module 3 (ADOS; (Lord et al., 2002)). The ADOS was administered by examiners who achieved research reliability under the supervision of a licensed clinical psychologist. Typically developing children were recruited within the same age range and language levels and had no reported psychiatric or medical diagnoses. No children in the TD group scored within the clinically elevated range for any domains or subdomains of the Child Behavior Checklist (Achenbach, 1991), including the domain related to pervasive developmental disorders, and no parents of typically developing children reported any concerns of ASD. Full demographic

characteristics of autistic and typically developing children can be found in Table 1. Parents provided written consent for their child to participate in the current study and children provided verbal assent about their willingness to participate, which was approved by the [institution name masked] institutional review board. The verbal assent was written in child-friendly language, without using any medical or academic jargon, at an appropriate comprehension level for kindergarteners with and without autism; children were informed that they could stop testing at any time. The children and their parents were informed about the purpose of the study (to understand how children learn), the procedures involved in

Table 1 Demographics of ASD and TD groups at timepoint 1

	ASD		TD	
	Number	%	Number	%
Sex*				
Male	21	75.0	12	42.9
Female	7	25.0	16	57.1
Race				
1. White/Caucasian	13	46.4	14	50.0
2. Black/African American	3	10.7	2	7.1
3. Asian	2	7.1	3	10.7
5. Biracial	6	21.4	7	25.0
6. Other	1	3.6	0	0
7. Native Hawaiian/Pacific Islander/Am. Indian	0	0	0	0
8. Unknown	3	10.7	2	7.1
Ethnicity				
Latino	11	39.3	7	25.0
Not latino	16	57.1	21	75.0
Maternal education				
1. Graduate school	11	39.3	14	50.0
2. Baccalaureate	10	35.7	10	35.7
3. Some college/associates degree	5	17.9	2	7.1
4. High school or GED	1	3.6	0	0
5. Unknown	1	3.6	2	7.1
	Mean (SD)	Range	Mean (SD)	Range
Age (mos)	64.64 (4.98)	56–79	64.29 (5.13)	54–76
NVIQ	108.71 (8.52)	92–126	113.18 (12.83)	85–156
VIQ	103.43 (12.23)	78–129	109.43 (10.67)	84–126
WJ-IV reading subtests				
Letter-word SS (T1)**	113.39 (17.77)	85–152	101.59 (13.87)	87–141
Pass comp SS (T1)	115.18 (14.81)	86–142	109.96 (11.81)	94–141
Letter-word SS (T2)	113.12 (17.61)	76–147	-	-
Pass comp SS (T2)	112.31 (13.43)	88–142	-	-
ERP diff score				
P1 diff score	0.04 (1.98)	- 5.72–4.45	- 0.08 (2.18)	- 5.45–5.13
P2 diff score	0.61 (2.63)	- 4.54–5.57	0.72 (2.52)	- 4.64–5.77

<0.05*, <0.01**

the study including the psychological testing and the EEG session, the potential risks (e.g., discomfort or boredom during the procedures) and measures being taken to prevent and respond to those risks (e.g., taking 10–15 breaks as needed, using snacks or other favorite activities and toys as reinforcements), potential benefits to themselves and others (helping families to better understand their child's strengths and weaknesses as well as the benefit to the larger population) and that their participation was completely voluntary and that they could withdraw at any time. They were also informed about confidentiality of data obtained from the study. There was no direct community involvement in the study although initially families provided verbal feedback on the procedures of the EEG data collection which was incorporated to refine the procedure (e.g., sending in pictures of the lab and other children carrying out the task in advance to the families so that they can prepare their children before the session). However, this was not done in a systematic way and the feedback was solicited informally.

The final sample (after exclusion described below) included 56 children in total: 28 with ASD (mean age at kindergarten entry = 64.64, $SD = 0.4.98$) and 28 TD children (mean age at kindergarten entry = 64.29; $SE = 5.13$) with usable EEG data. Few typically developing children completed year-end assessment due to COVID (the last cohort for ASD case completed T2 assessment in the Spring/Summer of 2019 for ASD, and the last cohort for TD cases was scheduled in the Spring/Summer of 2020 during which follow-ups were not feasible due to restrictions), thus more ASD cases were able to complete follow-up testing before the beginning of the COVID-19 pandemic), so longitudinal analyses were completed only for autistic children. The average NVIQ for the entire sample was 110.95, with 108.71 ($SD = 8.51$) for ASD group, and 113.18 ($SD = 12.83$) for the TD group. EEG data from 9 participants were excluded from final analyses as they did not meet criteria for minimum number of artifact-free EEG trials (described in more detail below).

Event-Related Potential (ERP) Measures

ERP task

EEG recordings were conducted in a testing room with minimal distractions. Children were provided with social stories before and during the EEG session and support from staff and parents during the net application. In advance of the EEG assessments, parents were informed about the procedures and asked to talk with their child about the session. All EEG assessments were conducted by a trained research assistant and began with a child-appropriate language explanation of the EEG data collection process. This setup process lasted between 10 and 15 min. In our work, we have

found that electrode application is fast and relatively comfortable for children as young as 3 years of age.

Auditory stimuli were presented with a PC laptop using E-Prime 2.0 software, via speaker at 85 SPL. Children were presented with two rhyming pseudowords/gibu/and/bidu/, recorded by a female native English speaker. The initial sensitization block consisted of one pseudoword repeated for 50 trials. The second block, which was used for analysis, was presented after a 20-s rest. This second block consisted of 100 pseudowords randomly presented, including 50 “new” pseudowords and 50 “old” pseudowords (i.e., already presented in the first block). Stimuli durations were 594 ms with a varied ISI of 1800 or 2800 ms.

EEG Recording, Data Reduction, and Data Processing

EEG data were collected with a 64-channel HydroCel Geodesic Sensor Net (Electrical Geodesics, Inc. (EGI), Eugene, OR, USA). The net was soaked in a potassium-chloride electrolyte solution before being placed on the participant's head.

EEG data were processed with MATLAB 2021b (The MathWorks, Natick, MA, USA) using the Maryland Analysis of Developmental EEG (MADE) Pipeline (Debnath et al., 2020). Data were downsampled to 256 Hz for speed of processing and corrected for a stimulus time offset of approximately 30 ms EEG data were digitally filtered (0.1 Hz high-pass, 50 Hz low-pass) and bad channels were removed using the FASTER tool (Nolan et al., 2010). To improve independent component analysis (ICA) decomposition, a copy of the data was created and filtered using a 1-Hz high-pass filter and segmented in 1-s epochs. ICA was used to detect and remove ocular and other artifacts. Data were then epoched to “old” and “new” events and baseline corrected using the 1-s period preceding stimulus onset. Finally, bad epochs, with voltage that exceeded ± 125 mV, were removed and interpolated using spherical spline interpolation. If more than 10% of channels were bad within an epoch, the entire epoch was removed. Any channels marked bad for more than 40% of the recording were interpolated. Participants with fewer than 20 “old” and 20 “new” events ($n = 9$) were excluded in line with previous research using this same paradigm in young children (Harwood et al., 2017), resulting in a final sample of 56 children. No participants had more than 10% of channels interpolated. On average, included participants had 39 “old” and 39 “new” epochs.

ERP Measures

As mentioned above, we focused here on the P1 and P2 components for analyses as these are prominent in children this age (Sharma et al., 1997; Silva et al., 2017) and both were visible in our grand average waveform; see Fig. 2. We also

examined the same patterns for the N2 component, which is related to speech sound processing in younger children (Gilley et al., 2005; Harwood et al., 2022; Sharma et al., 1997; Silva et al., 2017); N2 results are reported in the supplemental materials. All ERP components were quantified in an unbiased manner, using an a priori analysis location (cluster of frontocentral electrodes; see Fig. 1) and mean amplitude analysis time-windows defined based on the grand-average ERP (after collapsing across all conditions/participants; see Fig. 2).

Electrode locations (Fig. 1) were chosen based on previous literature with this paradigm (Harwood et al., 2022). The analysis time window for each component of interest was fixed across participants, with the specific time window employed for each component based on peaks within the grand-average ERP. We quantified the mean amplitude by centering a 50 ms (± 25 ms) analysis window on the first and second positive peaks (respectively) within the grand-average ERP. This resulted in the P1 being analyzed with a 30–80 ms window (55 ms peak) and the P2 being analyzed within an 85–135 ms window (110 ms peak). For the N2 component, we centered a 100 ms (± 50 ms) analysis

window on the most negative point, 240 ms (190–290 ms). These time windows are consistent with previous literature of children of this age (Gilley et al., 2005; Sharma et al., 1997; Silva et al., 2017).

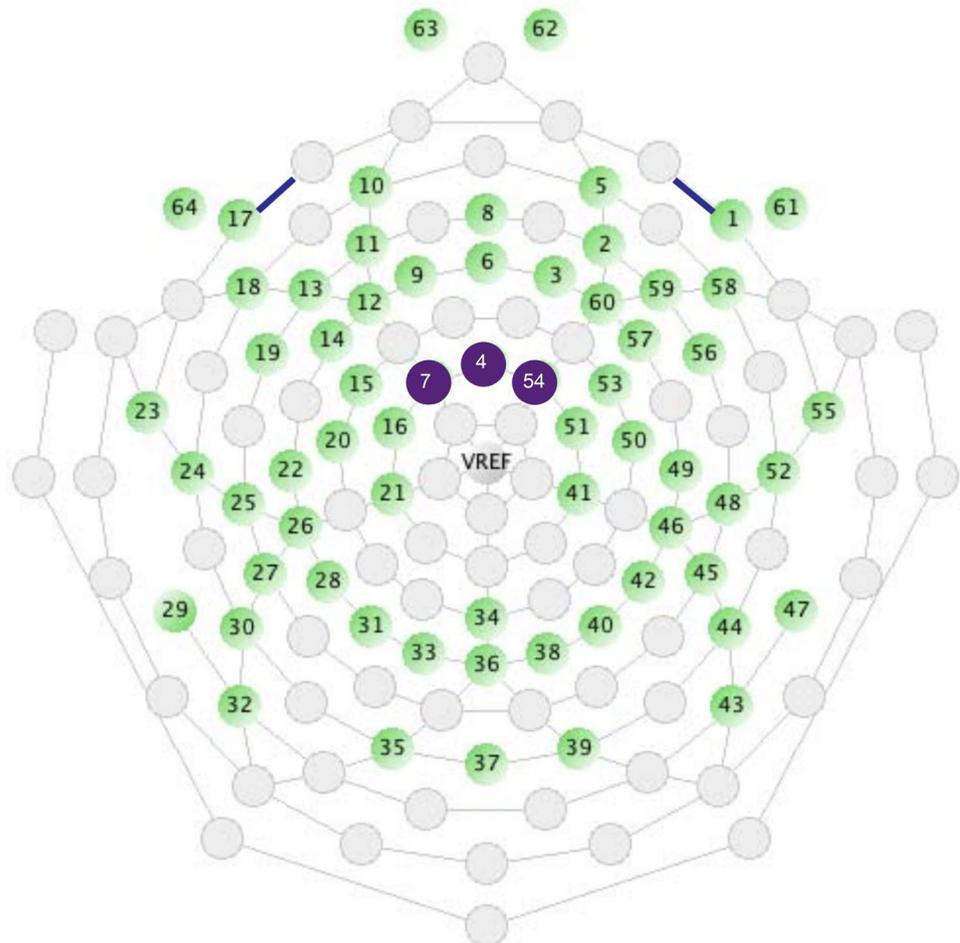
Behavioral Measures

All behavioral testing was done in a child-friendly environment while using various reinforcement strategies (e.g., using frequent breaks and snacks to sensitively respond to the needs of the children) to maximize motivation and engagement. All testing was delivered by trained staff and was supervised by a clinical psychologist who has extensive experience working with young children with ASD.

Reading Achievement

Reading achievement was assessed using the Standard Scores of Letter-Word Identification (word recognition/decoding) and Passage Comprehension (reading comprehension) subtests of the Woodcock-Johnson III (WJ-IV) (Woodcock et al., 2001). In the Letter-Word Identification

Fig. 1 Cluster of Fronto-Central electrodes used for analysis



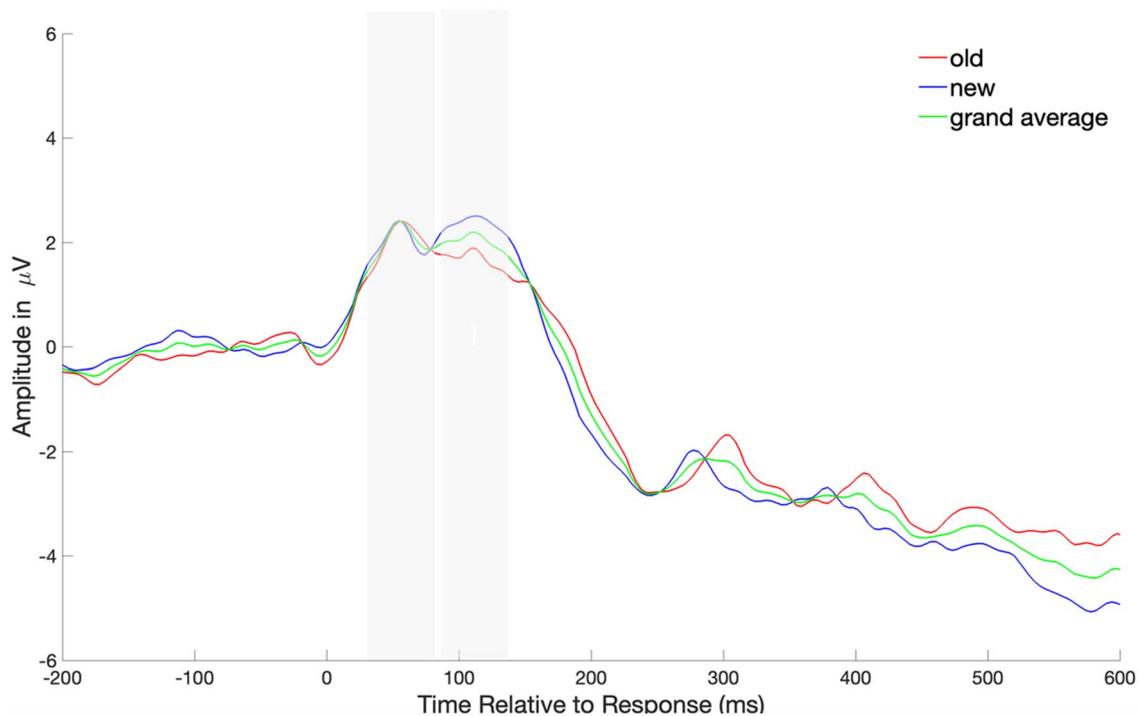


Fig. 2 Grand average waveform

subtest, children are asked to read aloud from an increasingly difficult list of letters and vocabulary words. For the Passage Comprehension subtest, children are asked to read a sentence silently and then decide on the word needed to complete the sentence (Woodcock et al., 2001); in very early items children are asked to identify pictures. We examined both abilities as many autistic children may have intact letter-word identification skills but more limited reading comprehension (Kim et al., 2018), and because phonological processing may contribute to weakness in both areas (Åsberg Johnels et al., 2019). Children completed the assessments at kindergarten entry (mean age = 64.59 months) and exit (mean age = 73.36 months).

Cognitive Skills

Cognitive functioning (verbal and nonverbal IQ) was measured using the Differential Ability Scale (DAS; Elliott, 2007). Nonverbal IQ (NVIQ) was used for analyses because it has been found to be a more stable measure of intellectual functioning in autistic children (Bishop et al., 2015).

Statistical Analyses

In our first set of analyses, we conducted Generalized Linear Mixed Models (GLMM) in R (R Core Team, 2022) to examine (1) group differences in neural speech sound processing

at kindergarten entry and (2) relations with concurrent reading ability (i.e., word recognition and comprehension skills). Then, using longitudinal analyses, we (3) examined whether old/new ERP difference scores were predictive of year-end reading ability in kindergarteners with ASD. Note, longitudinal analyses focused only on children with ASD because the majority of typically developing children did not complete year-end sessions due to the emergence of the COVID-19 pandemic (see Participants above for more detail).

Concurrent Analyses

To examine whether there was a group difference in ERP amplitudes for “old” and “new” speech sounds at kindergarten-entry, we employed a GLMM with P1 component amplitude as the dependent variable and a GLMM with P2 component amplitude as the dependent variable. We included stimulus (“new” vs. “old”) group (ASD vs. typical), and their interaction as independent variables, in order to explore whether “new” vs. “old” stimulus processing differed for children with ASD compared to typically developing children. All analyses controlled for sex, NVIQ and age.

In the next step, for each model described above, we added WJ-IV standard scores as independent variables to examine whether the neural processing of “new” vs. “old” speech sounds differed for children with ASD and typically developing children as a function of reading skills.

Specifically, we added 3-way interactions between group, stimulus, and each WJ-IV standard score; separate interaction terms were added for Letter-Word Identification WJ-IV score (word recognition/decoding ability) and Passage Comprehension WJ-IV score (comprehension ability). All analyses controlled for sex, NVIQ and age.

We conducted a power analysis using G*Power version 3.1 (Faul et al., 2007) to ensure a sufficient sample size for our planned analyses. With a significance criterion of $\alpha=0.05$ and power=0.80, the minimum total sample size needed to detect a medium effect (effect size $f=0.20$) was 32 for the planned two-way interaction (2 groups, 2 measurements, 0.70 correlation among repeated measures) and 48 for the planned three-way interaction (4 groups, 2 measurements, 0.70 correlation among repeated measures).

Longitudinal Analyses

To examine whether old/new difference scores at kindergarten-entry predicted reading skills at kindergarten-exit in children with ASD, we conducted regression analyses with WJ-IV Letter-Word Identification and Passage Comprehension Standard Scores as outcome measures. In two separate models, P1 or P2 old/new difference scores (new-old) were employed as predictors, while controlling for sex and NVIQ. Longitudinal analyses focused only on children with ASD.

Results

Question 1 At kindergarten entry, do children with ASD significantly differ in neural processing of speech sounds (“new” vs. “old”) compared to typically developing children?

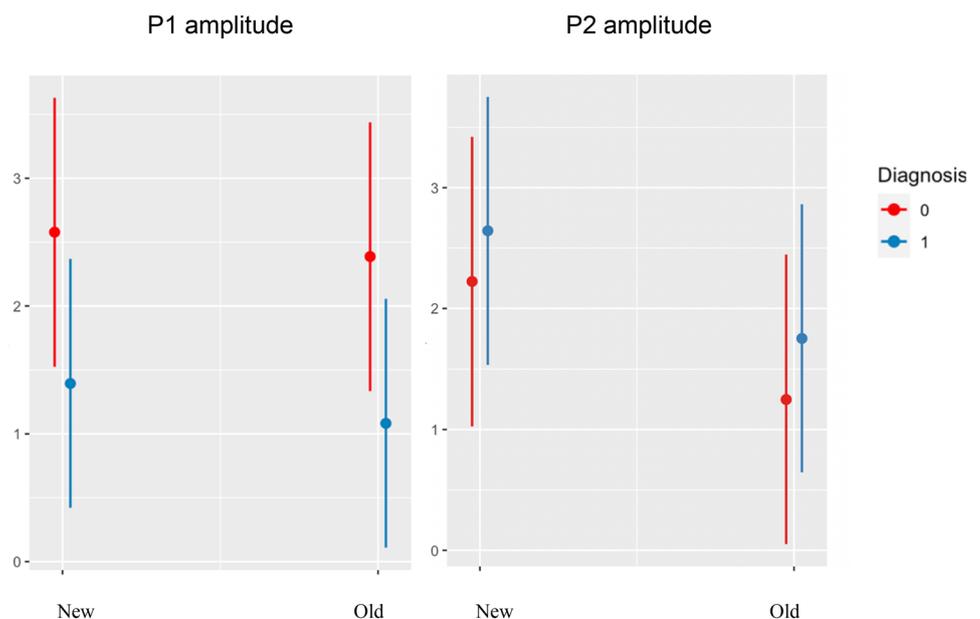
P1 Amplitude

To answer our first question, we examined the 2-way interaction of group (ASD vs. TD) and stimulus (“new” vs. “old”). In our model using P1 amplitude as the dependent variable, there was no significant interaction between group and stimulus ($F_{1,54}=0.02$, $p=0.89$, partial $\eta^2=0.00$), indicating that children with ASD and typically developing children showed similar P1 amplitudes for “new” vs. “old” stimuli (Figs. 3 & 4). Results did reveal a main effect of group ($F_{1,51}=4.12$, $p=0.05$, partial $\eta^2=0.07$); on average, children with ASD had lower P1 amplitudes compared with typically developing children. There was no significant main effect of stimulus ($F_{1,54}=0.01$, $p=0.97$, partial $\eta^2=0.00$).

P2 Amplitude

With P2 amplitude as the dependent variable, there was no interaction between stimuli and group ($F_{1,54}=0.03$, $p=0.87$, partial $\eta^2=0.00$) in our models, indicating that children with ASD and typically developing children showed similar P2 amplitudes for “new” vs. “old” stimuli (Figs. 3 & 4). Results revealed a trend for a main effect of stimulus ($F_{1,54}=3.61$, $p=0.06$, partial $\eta^2=0.06$); on average, P2 amplitudes were greater for “new” stimuli

Fig. 3 Predicted amplitude values for “new” and “old” stimuli for children with and without ASD. Plots controlling for age, sex, and NVIQ



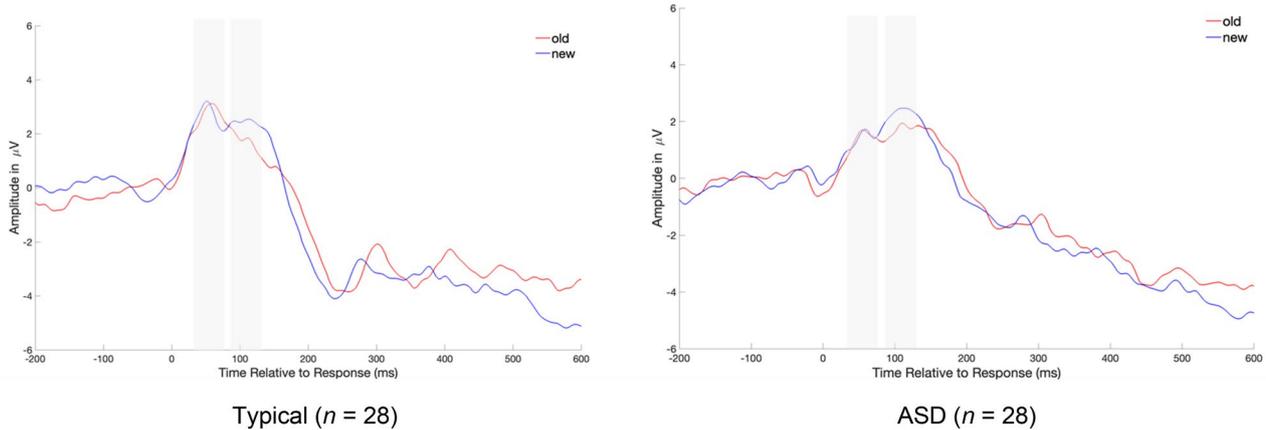


Fig. 4 Waveforms for ASD and typical groups

compared to “old” stimuli. There was no significant main effect of group ($F_{1,51} = 0.26$, $p = 0.61$, partial $\eta^2 = 0.01$).

Question 2 At kindergarten entry, is neural processing of speech sounds related to reading skills (word recognition and reading comprehension)?

P1 Amplitude

To answer our next question, we included WJ-IV standard scores to explore the 3-way interaction between group, stimulus, and each WJ-IV standard score. Using P1 amplitude as the dependent variable, results revealed a 3-way interaction between stimulus, group, and the WJ-IV Letter-Word ID standard score ($F_{1,51} = 4.00$, $p = 0.05$, partial $\eta^2 = 0.07$). Similarly, a significant 3-way interaction was also identified between stimulus, group, and WJ-IV Passage Comprehension standard score ($F_{1,51} = 4.42$, $p = 0.04$, partial $\eta^2 = 0.08$). To further examine these three-way interactions, we conducted paired samples T-tests comparing P1 amplitude for “new” vs. “old” stimuli for “lower” and “higher” readers with ASD, defined via median split (Fig. 5). Among children with ASD with lower Letter-Word ID, P1 amplitude was greater for “new” compared to “old” stimuli; however, this difference was marginally significant ($p = 0.07$). For children with ASD with lower Passage Comprehension standard scores there was no significant difference in P1 amplitude between “new” vs. “old” stimuli ($p = 0.31$). For children with ASD with higher Letter-Word ID and higher Passage Comprehension standard scores, the P1 amplitude difference for “new” vs. “old” stimuli was marginally significant for Letter-Word ID ($p = 0.08$) but not Reading Comprehension ($p = 0.56$).

P2 Amplitude

For P2 amplitude, results revealed a trend for a 3-way interaction between stimulus, group, and WJ-IV Letter-Word ID standard score ($F_{1,51} = 3.67$, $p = 0.06$, partial $\eta^2 = 0.07$) but not for the 3-way interaction between stimulus, group, and WJ-IV Passage Comprehension standard score ($F_{1,51} = 2.29$, $p = 0.14$, partial $\eta^2 = 0.04$). Thus, we further examined the three-way interaction between stimulus, group, and WJ-IV Letter-Word ID standard score using paired T-tests, comparing P2 amplitude for “old” and “new” stimuli for “lower” as well as “higher” readers with ASD, defined via median split (Fig. 5). For children with ASD with lower Letter-Word ID standard score, P2 amplitude was significantly greater for “new” compared to “old” stimuli ($p = 0.04$), but for children with ASD with higher Letter-Word ID, there was no significant difference in P2 amplitude between stimuli ($p = 0.70$).

Question 3 In children with ASD, will neural processing of speech sounds predict end of kindergarten reading skills?

P1 Amplitude

Finally, our longitudinal model predicting year-end reading skills in kindergarteners with ASD using old/new P1 difference score was also significant, $R^2 = 0.28$, $F(3,22) = 4.18$, $p = 0.02$. We found a significant effect of old/new P1 difference score ($t = -2.10$, $p = 0.05$) on end of year Letter-Word ID standard score (Table 2), after controlling for NVIQ ($t = 0.59$, $p = 0.56$) and sex ($t = -1.56$, $p = 0.14$). Smaller old/new P1 difference scores were associated with higher Letter-Word ID standard scores at year end (Fig. 6). There was no significant effect of old/new P1 score ($t = -0.99$, $p = 0.34$) on WJ-IV Passage

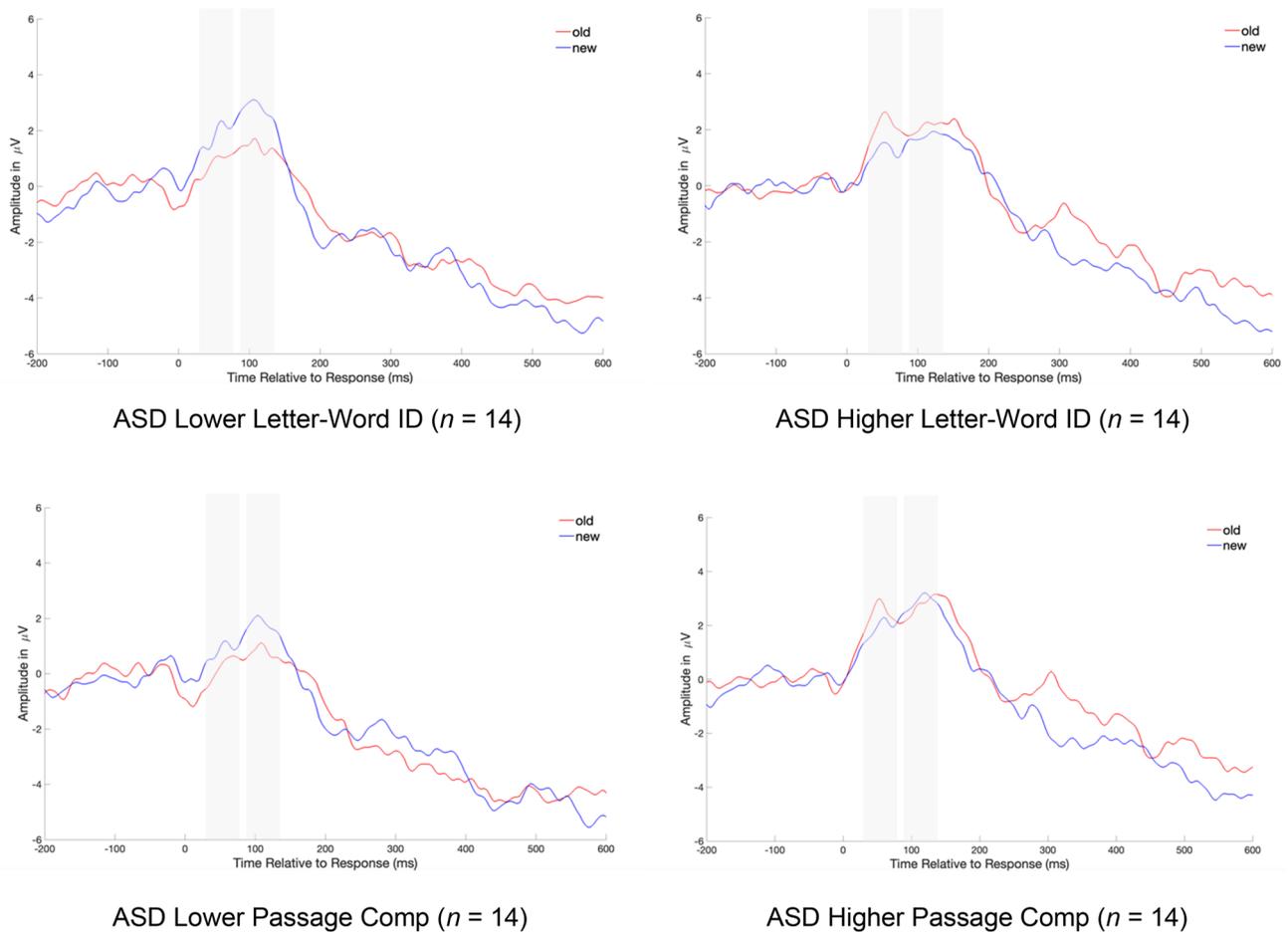


Fig. 5 Waveforms for lower and higher reading groups for children with ASD

Comprehension standard score in our second model, controlling for the effects of NVIQ ($t = 1.34$, $p = 0.19$) and sex ($t = -1.14$, $p = 0.27$).

P2 Amplitude

Our longitudinal model predicting year-end reading skills in kindergarteners with ASD using old/new P2 difference score was significant, $R^2 = 0.29$, $F(3,22) = 4.43$, $p = 0.01$. We found a significant effect of old/new P2 difference score ($t = -2.24$, $p = 0.04$) on end of year WJ-IV Letter-Word ID standard score (Table 2), after controlling for NVIQ ($t = 0.51$, $p = 0.61$) and sex ($t = -2.23$, $p = 0.04$). Smaller old/new P2 score difference was associated with higher Letter-Word ID standard score at year-end (Fig. 6). There was no significant effect of old/new P2 score ($t = -1.13$, $p = 0.27$) on WJ-IV Passage Comprehension standard score, controlling for the effects of NVIQ ($t = 1.29$, $p = 0.21$) and sex ($t = -1.47$, $p = 0.16$).

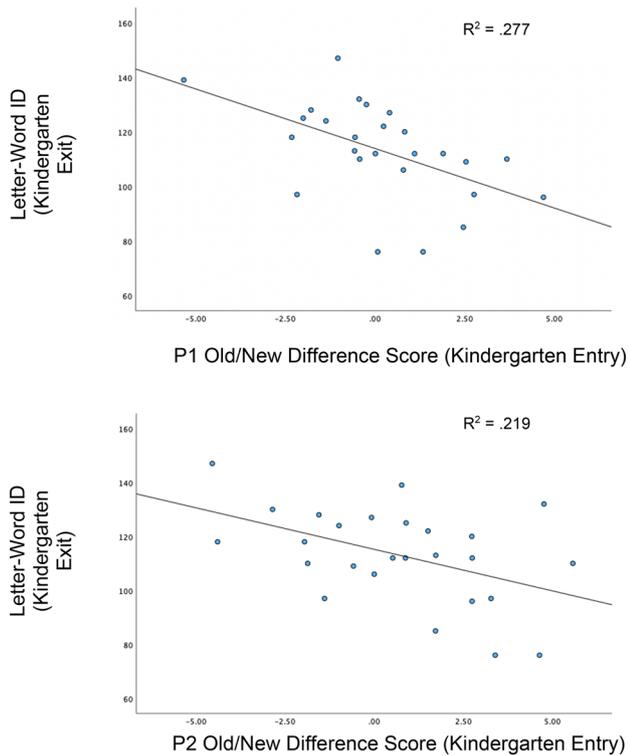
Discussion

This study examined patterns of neural processing of speech sounds (rhyming, bisyllabic pseudowords) in a group of verbal children with ASD and their relation to reading skills at kindergarten entry and exit. Although previous ERP studies have examined auditory processing differences in autistic populations (Chen et al., 2020; Donkers et al., 2015; Guiraud et al., 2011; Hudac et al., 2018; Ruiz-Martínez et al., 2020; Schwartz et al., 2018), including their relation to oral language ability (Matsuzaki et al., 2019; Russo et al., 2009), this study is a first to examine the relation between neural processing of speech sounds and reading skills (word recognition and reading comprehension) in kindergarteners with ASD.

Results revealed that autistic kindergarteners in this sample demonstrated smaller P1 and N2 components compared to similarly cognitively able typically developing children. This replicates previous research suggesting

Table 2 Regression analyses of old/new difference predicting year-end (a) letter-word standard score and (b) passage comprehension standard score

Outcome: year-end letter-word standard score	Predictors	B	SE	t(df)	Significance	R ²
Model 1	NVIQ	0.21	0.35	0.59(22)	0.56	0.28
	Sex	- 11.95	7.71	- 1.55(22)	0.14	
	P1 Diff. Score	- 3.27	1.56	- 2.10(22)	0.05	
Model 2	NVIQ	0.18	0.34	0.51(22)	0.61	0.29
	Sex	- 15.77	7.10	- 2.23(22)	0.04	
	P2 Diff. Score	- 2.54	1.13	- 2.24(22)	0.04	
Outcome: year-end passage comprehension	Predictors	B	SE	t(df)	Significance	R ²
Model 1	NVIQ	0.39	0.29	1.34(22)	0.19	0.12
	Sex	- 7.36	6.47	- 1.14(22)	0.27	
	P1 Diff. Score	- 1.29	1.31	- 0.99(22)	0.34	
Model 2	NVIQ	0.38	0.29	1.29(22)	0.21	0.13
	Sex	- 8.77	5.96	- 1.47(22)	0.16	
	P2 Diff. Score	- 1.08	0.95	- 1.13(22)	0.27	

**Fig. 6** Scatterplot showing relation between kindergarten entry **A** P1 and **B** P2 ERP Old/new difference score (new-old) and kindergarten exit letter-word identification standard score

that autistic children have attenuated early ERP responses (Chen et al., 2020; Donkers et al., 2015; Dwyer et al., 2021; Guiraud et al., 2011; Hudac et al., 2018; Ruiz-Martínez et al., 2020). There were no significant main effects of P2 amplitude in this sample.

Results also revealed that autistic children with lower reading skills had larger P1 and P2 amplitude responses to “new” vs. “old” speech sounds when compared to autistic peers with higher reading skills and typically developing children. P1 and P2 difference scores were significantly associated with year-end word recognition (controlling for sex and NVIQ), with smaller old/new difference scores associated with better reading outcomes. These results are in the opposite direction as predicted based on similar work with this old/new paradigm and related paradigms (e.g., MMN), which have shown that better auditory discrimination skills (larger neural responses to deviant vs. standard & “new” vs. “old” stimuli) are associated with better linguistic skills (Gu & Bi, 2020; Harwood et al., 2022; Schwartz et al., 2018). Here, however, we found that *lower* reading ability in the ASD group was associated with greater P1/P2 amplitudes for “new” compared to “old” stimuli. Interestingly, our P1/P2 findings were most similar to children categorized as “lower language” in the Harwood et al., (2022) sample rather than “low language”, who also demonstrated patterns of higher P1 responses to “new” vs. “old” stimuli, albeit non-significant.

One potential explanation for this unexpected result is that greater P1/P2 amplitudes for “new” compared to “old” stimuli in autistic children with lower reading ability may indicate greater neural effort needed to encode “new” or unlearned acoustic information, which was significantly associated with more limited, concurrent and longitudinal word recognition ability. A second explanation is that greater P1/P2 amplitudes for “new” vs. “old” stimuli reflect enhanced sensory processing in ASD, also noted in other sensory domains (e.g., bias for processing local vs. global visual information; Happé & Firth, 2006; Lepistö et al., 2008). Enhanced sensory processing is not necessarily an advantage in linguistic development, as disproportionate attention to changes in lower-level acoustic features may interfere with the encoding of more important, phonetic information. This pattern of findings is more commonly reported for the N2 and MMN components; greater MMN responses to “deviant” vs. “standard” stimuli have been reported in autistic children in some studies (Lepistö et al., 2008; Matsuzaki et al., 2019) and enhanced N2 responses to “new” vs. “old” stimuli have been reported in children with language delay (Harwood et al., 2022). However, this is the first study to relate enhancement of P1/P2 components to “new” vs. “old” speech sounds and lower reading ability in children with ASD.

Furthermore, although we found stimulus*group*reading ability differences for P1 and P2 components, we found no significant associations here between N2 amplitude for “new” vs. “old” stimuli and reading ability (word recognition or reading comprehension) regardless of diagnosis (see supplemental analyses). Thus, it is difficult to disentangle the effects of phonemic discrimination and change detection from more domain-general auditory processing in this pattern of findings. One previous study aimed to isolate acoustic vs. speech sound information processing in autistic children by manipulating a combination of speech sound and acoustic information in an MMN paradigm (Lepistö et al., 2008). The authors found that autistic children showed greater MMN responses to deviant speech and nonspeech sounds; however, this effect was no longer significant when deviant speech stimuli also included changes in acoustic features, suggesting that acoustic information processing could interfere with speech sound processing.

Furthermore, previous work with this old/new paradigm did find “new” vs. “old” differences in the N2 component in younger toddlers with and without language delay (Harwood et al., 2022). Our sample differed in linguistic ability from this sample. Here, no autistic children scored below a standard score of 77 for either word recognition or reading comprehension, whereas the Harwood et al. (2022) sample included children with significant language delay (standard scores as low as 56). Thus, it may be that this paradigm is most sensitive to indexing phonemic discrimination and

change detection reflected by N2 in younger children and those with more pronounced language-based impairments. In addition, we did not see a significant difference in N2 amplitude between “new” vs. “old” phonemic stimuli in typically developing children of any reading ability, which again may be because our sample was limited to only typically developing children with reading ability within the average range (standard scores > 85) to match the reading ability of the ASD group.

Limitations and Future Directions

As this study was the first to examine the neural processing of speech sounds and reading ability in kindergarteners with ASD there were some important weaknesses. First, we were able to gather data longitudinally, but the sample size was modest with 56 children including 28 with ASD (sufficient to detect a moderate effect) with average to above average cognitive and language skills, as goal of the larger study was to examine academic achievement in autistic children without intellectual impairment. Results should be replicated within larger, more representative samples of children with ASD with a greater range of nonverbal and verbal abilities to fully explore patterns of neural processing of speech sounds in ASD. This is especially important in light of our finding that autistic children with lower reading ability showed patterns similar to the “lower” but not “low” language group reported in Harwood et al. (2022). Furthermore, in our sample, several children with ASD as well as most typically developing children were not able to complete post-kindergarten assessment due to the emergence of the COVID-19 pandemic. Future research should consider collecting longitudinal data on autistic and non-autistic children to fully examine the longitudinal changes in these neural markers.

Furthermore, the paradigm used in this study differs from many previous ERP studies of autistic children. While we can make some general comparisons to prior findings, more direct comparisons are difficult with the limited body of current research. Most ERP studies of speech sound processing in autism use an oddball design and examine MMN responses (Kasai et al., 2005; Key & Slaboch, 2021; Key et al., 2016; Ludlow et al., 2014). While prior work has used this old/new paradigm to answer questions about speech sound processing and language-based skills, this prior work tested younger children with language delay who were not autistic (Harwood et al., 2017, 2022). Therefore, the current study is an important first step towards extending ERP research methodologies used in related populations (e.g. children with language delay, reading disabilities) to answer questions about academic achievement in ASD.

Finally, as previously reported, experimental stimuli in this paradigm were not counterbalanced, so it is difficult to fully disentangle the effects of stimulus learning from the

encoding of acoustic/phonetic information (Harwood et al., 2022), which is important as we observed “new” vs. “old” differences for P1 and P2 components but not the N2 component. A larger sample size with a wider range of language and reading abilities may also be needed to fully examine differences in the N2 component. This is especially critical as many early ERP studies of autistic children have also shown inconsistencies across samples and paradigms (Gu & Bi, 2020; Schwartz et al., 2018).

Clinical Implications

Findings from this novel first examination of neural processing of speech sounds and reading ability in autistic children have several important clinical implications. First, although previous work has investigated auditory processing in autistic populations, including in paradigms that use phonemic stimuli, no previous work has examined how differences in the neural processing of speech sounds relate to reading development in autistic children. This is a critical gap in the literature as impairments in auditory processing have been shown to relate to phonological development in other populations (e.g., dyslexia, language disorders, etc.) but studies on this phenomenon are still limited in autistic children, especially at the kindergarten age when children are first learning to read. Furthermore, behavioral literature has demonstrated phonological processing weaknesses in at least a portion of autistic children (Åsberg Johnels et al., 2019; Newman et al., 2007; Tager-Flusberg, 2006). Our results further extend this hypothesis, suggesting that autistic kindergarteners, particularly those with lower reading ability, process speech sounds differently at a very early neural time course.

By examining how autistic children differ in the processing of speech sounds at a neural level, we can work towards better understanding the varying profiles of reading ability in ASD and work towards isolating targets of early intervention. Because autistic children may start to show different patterns of phonological processing, even before their formal education starts, intervention supporting phonological skills prior to kindergarten entry could be crucial in promoting reading achievement, particularly word recognition skills, for autistic children through the kindergarten year and possibly beyond. Furthermore, not all autistic children show difficulties with reading and thus early identification of those who need intervention is critical at this developmental period. Utilizing early neural markers of phonological weakness may help us identify which children may have the most challenges learning to read down the road and enable us to provide additional academic support during the critical preschool years, when neuroplasticity is at its greatest (Vicari et al., 2000).

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Author contributions Brittany L. Manning: Writing – review & editing, Writing – original draft, Formal analysis. Kianoosh Hosseini: Writing – review & editing, Software. Eunjin Yang: Writing - review & editing, Writing - original draft. George A. Buzzell - Writing – review & editing, Software. Nicole Landi - Writing – review & editing, Conceptualization, Methodology. So Hyun Kim - Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization, Methodology.

Declarations

Competing Interests All authors report no competing interests.

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