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Phonetic discrimination mediates the relationship between auditory brainstem response stability and syntactic performance

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ABSTRACT

Syntactic, lexical, and phonological/phonetic knowledge are vital aspects of macro level language ability. Prior research has predominantly focused on environmental or cortical sources of individual differences in these areas; however, a growing literature suggests an auditory brainstem contribution to language performance in both typically developing (TD) populations and children with autism spectrum disorder (ASD). This study investigates whether one aspect of auditory brainstem responses (ABRs), neural response stability, which is a metric reflecting trial-by-trial consistency in the neural encoding of sound, can predict syntactic, lexical, and phonetic performance in TD and ASD school-aged children. Pooling across children with ASD and TD, results showed that higher neural stability in response to the syllable /da/ was associated with better phonetic discrimination, and with better syntactic performance on a standardized measure. Furthermore, phonetic discrimination was a successful mediator of the relationship between neural stability and syntactic performance. This study supports the growing body of literature that stable subcortical neural encoding of sound is important for successful language performance.

1. Introduction

Language acquisition is a complex task, yet common developmental stages, strategies, and phenomena (e.g., ease and lack of explicit instruction) are readily identifiable in children (Hoff, 2014). However, individual trajectories and outcomes vary, as even children within the typical range of verbal skills are not identical in language performance (Lieven, Pine, & Barnes, 1992; Nelson, 1981). Likely sources of this variation include both environmental (e.g., Huttenlocher, Waterfall, Vasilyeva, Vevea, & Hedges, 2010) and neurological factors (e.g., Golestani, 2014), the latter of which are the focus of the current study. Individual differences in cortical brain structures and functions have been linked to diverse language abilities observed in children (Lee et al., 2007; Richlan, Kronbichler, & Wimmer, 2013; Salvan et al., 2017; Skeide et al., 2016); however, while most investigations to date have examined cortical rather than subcortical structures and processes, we follow recent proposals that examining the subcortical processing of speech is also critical. The current study investigates what we call the Auditory Stability Hypothesis (Anderson, Parbery-Clark, Yi, & Kraus, 2011; Anderson, Skoe, Chandrasekaran, Zecker, & Kraus, 2010; Banai et al., 2009; Hornickel & Kraus, 2013; Skoe, Krizman, & Kraus, 2013; Neef, Müller, et al., 2017; Skoe, Brody, & Theodore, 2017) which proposes that unstable neural encoding of sound early in the auditory neural pathway, (i.e., increased variability in the neural response to an auditory stimulus) may cascade into difficulties in macro level language abilities. We extend this hypothesis in three ways: First, we test whether subcortical auditory processing is related to performance on lexical and syntactic tasks in school age children. Second, we test the degree to which phonetic discrimination mediates the observed relationships, and third, we compare these effects in typically developing (TD) children and children with Autism Spectrum Disorder (ASD).

1.1. *Variability in language Development: Etiological, environmental and cortical contributions*

Language learning is a heterogeneous enterprise influenced by multiple factors (Fernald, Marchman, & Weisleder, 2013; Goldstein & Schwade, 2008; Leonard & Hill, 2014; Newman, Rowe, & Bernstein Ratner, 2016; Weisleder & Fernald, 2013). Etiology clearly plays a significant role, as children with neurodevelopmental disorders such as ASD, which is diagnosed based on the presence of social, communication, and behavioral differences (American Psychiatric Association,

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2013), vary in language development rate, patterning, and outcome, from being equivalent to TD children to minimally verbal (Kjelgaard & Tager-Flusberg, 2001; Naigles & Chin, 2015). Richness of caregiver input, including the use of a more varied vocabulary and more diverse grammatical formations, also predicts complexity of subsequent language production, both in TD children and children with ASD (Fusaroli, Weed, Fein, & Naigles, 2019; Goodwin, Fein, & Naigles, 2015; Nadig & Bang, 2017). Functional maturation of the cortex has also been linked with processes of language development (Friederici & Skeide, 2015), as TD children and adolescents with more mature gray and white matter structures in language-relevant brain regions have been reported to perform better on concurrent language tasks, as well as on lexical and grammatical tasks measured later in development (Lee et al., 2007; Richlan et al., 2013; Salvan et al., 2017; Skeide et al., 2016). Moreover, variability in the language processing and performance of children with ASD has been linked to variability in the maturation of very similar cortical structures and processes as seen in TD children (Joseph et al., 2014; Lombardo et al., 2015; Nagae et al., 2012; Naigles et al., 2017).

These and other similarities of development, outcome, environmental, and cortical influences with respect to language, have led Tomblin (2015) to place the atypical language development observed in such disorders as ASD at one end of the entire developmental spectrum for language, rather than as instantiating completely different language learning phenomena compared to TD children. We concur with this approach, and so include both TD children and children with ASD in the current study with the primary motivation of more easily detecting relationships between children's neural processing of sound and their language development, given the greater spread of language performance that will be available in a more heterogeneous sample. A secondary motivation is to continue the exploration of how the neural processing of language might differentiate TD and ASD groups at the subcortical level, as subcortical processing, compared to cortical processing, is less affected by attentional processes and provides more fine-grained temporal resolution of auditory stimuli (Skoe & Kraus, 2010).

1.2. Subcortical contributions to language and language development

Recent research has begun to illuminate how subcortical neural activity might contribute to language development and performance (Burgaleta, Sanjuan, Ventura-Campos, Sebastian-Galles, & Avila, 2016; Chandrasekaran, Kraus, & Wong, 2012; Ketteler, Dastrau, Vohn, & Huber, 2008). In the current paper, we focus exclusively on the Auditory Brainstem Response (ABR), an auditory evoked potential recorded from scalp electrodes. ABRs are the result of electrical potentials generated by the synchronous activity of neurons within the auditory nerve, cochlear nucleus, superior olivary complex, lateral lemniscus and inferior colliculus (for a review see Hall, 2006) that emerge as a series of peaks within the first 10 ms after the onset of stimulation. ABRs are low voltage signals from deep brain sources; to emerge from the noise floor, responses to hundreds, if not thousands, of stimulus presentations are averaged. The most common stimulus used to elicit ABRs is a short click, and the latency of Wave V, the most robust component of the onset response, is the most common measure. ABRs can also be recorded to complex sounds such as the widely used syllable /da/, which incorporates both transient and sustained acoustic elements, and is a better approximation of speech than a click stimulus (Skoe & Kraus, 2010). Both click Wave V and speech-evoked responses have been traced to the inferior colliculus as the primary generator (Hall, 2006; Chandrasekaran & Kraus, 2010).

Extensive research has established a body of age and gender norms of ABR measures; given the extremely short timeframe and voltage, even the smallest divergence from these norms can be meaningful for behavioral functioning (Skoe, Krizman, Anderson, & Kraus, 2015). For example, the timing of brainstem encoding has been found to be associated with language performance, with longer latencies to /da/ during childhood being associated with poorer reading, spelling, and phonological awareness (Banai et al., 2009; Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009; Wible, Nicol, & Kraus, 2004). Moreover, children with grammatical impairments manifest longer ABR latencies to /da/ at faster stimulus rates (those over 30 Hz) (Basu, Krishnan, & Weber-Fox, 2010; Gabr & Darwish, 2016), and individuals with ASD manifest longer ABR latencies to speech stimuli compared with TD controls (Courchesne, Courchesne, Hicks, & Lincoln, 1985; Rumsey, Grimes, Pikus, Duara, & Ismond, 1984; Russo et al., 2008; Russo, Nicol, Trommer, Zecker, & Kraus, 2009; Tharpe et al., 2006). Interestingly, though, connections between individual differences in ABR latency and individual differences in language performance in children with ASD have only rarely been investigated; this absence was one motivation to include children with ASD in this test of the Auditory Stability Hypothesis.

Recent trends in the study of ABRs have converged on the idea that the stability of subcortical processing of sound has a cascading effect on language functioning (Hornickel & Kraus, 2013; Hornickel, Anderson, Skoe, Yi, & Kraus, 2012; Skoe, Krizman, Spitzer, & Kraus, 2013; Wible, Nicol, & Kraus, 2002; Neef, Müller, et al., 2017). We now designate this as the Auditory Stability Hypothesis, which proposes that unstable neural processing, indexed by a lack of consistency of neural encoding from one instance of a speech sound to the next, interferes with the ability to form a stable representation of the auditory world, which in turn negatively affects higher-level functions that depend on the neural signal, such as language (Hornickel & Kraus, 2013; Skoe et al., 2013; Tecoulesco, Skoe, & Naigles, 2018). For example, if sounds or words are not consistently encoded the same way, then the representations that ensue might be 'fuzzy', analogous to what a person hears when listening to someone talking in a noisy environment or across a poor telephone connection. Children with fuzzy representations of even commonly heard words may need to hear more repetitions to understand what was said, because the fuzzy representations are not clear enough to enable immediate and successful recognition and understanding. This lack of precision is likely to slow down the language learning process, possibly at multiple levels (phonetic, lexical, syntactic).

Using the approach outlined in previous work (Hornickel & Kraus, 2013; Skoe & Kraus, 2010), we operationally define neural response stability as the degree of linear relationship between two ABR waveforms recorded to the same repeated stimulus. For example, two sets of 3000 responses to /da/ are collected and each averaged to produce two average response waveforms, with each subaverage representing a time-series. A linear relationship is then calculated for the two averaged waveforms to determine their similarity. Responses with high stability (i.e., with correlation values approaching 1.0) show similar ABR waveform morphology across repeated recordings within a test session. On the other hand, responses with greater test–retest variability are characterized by low stability (correlation values approaching 0.0), suggesting the same sound stimulus is engendering neural responses with different temporal characteristics. Data from animals' models supports this characterization by showing that low neural stability measured from scalp electrodes reflects increased trial-by-trial variation in intracellular brainstem activity. While ABRs are too noisy to be analyzed at the level of the individual trial, we can infer from these single-trial intracellular recordings that measurements of neural stability of human brainstem activity made from the scalp reflect trial-by-trial consistency in the neural response and not neural adaptation to repeated stimulation or an ordering effect (White-Schwoch, Nicol, Warrier, Abrams, & Kraus, 2017). Further support for neural response stability as a measure of trial-by-trial variation comes from studies of children and adolescents showing that calculations of neural response stability are virtually the same when made using random samples of trials in a recording, interleaved trials within a recording, or separate recordings (as done here); (Hornickel & Kraus, 2013; Krizman, Skoe, Marian, & Kraus, 2014; Krizman & Kraus, 2019). A growing number of findings have reported differences in ABR stability between typical and atypical groups of school age children, as well as associations between ABR stability and language performance. For example, children with reading difficulties have been found to show less stable neural responses to the speech sounds /ba/ and /ga/, compared with poor readers (Hornickel & Kraus, 2013). Similarly, Neef, Müller, et al. (2017) examined the ABR to a 170 ms /da/ in a study of dyslexia risk genes, and reported that after controlling for age, gender, family risk, and IQ, children with greater numbers of risk alleles of KIAA0319 showed less stability in their neural responses. More precise relationships with language were not reported.

With respect to studies including children with ASD, Russo and colleagues (2009) found their ASD group to have less ‘fidelity to the stimulus’ than their TD group. In this study, the responses were compared to the stimulus waveform itself. This is arguably a less direct approach to calculating neural stability than comparing subaverages of the response; however, more faithful responses to the stimulus can also be taken to indicate better stability. Russo et al. (2009) also reported that TD children and children with ASD who showed more ‘faithful’ responses to /da/ in a noise condition had higher core and receptive language performance on a standardized test. Because no visualization of the correlation (e.g., scatterplot) between /da/ stability and language measures was provided, the precise nature of this relationship is currently unknown. Finally, Otto-Meyer and colleagues (2018) investigated neural stability in a subset of the child participants in Russo et al. (2009), comparing stability of ABRs to three speech stimuli (/da/, rising pitch /ya/ and falling pitch /ya/). They reported that the overall stability of the neural responses was consistently and significantly greater for the TD group, compared to the ASD group (Otto-Meyer, Krizman, White-Schwoch, & Kraus, 2018). Similar to Neef, Müller, et al. (2017), this report included no comparisons to language measures, although connections were drawn to language outcomes when interpreting results.

In sum, current research has found intriguing indications that ABR stability varies between children with ASD vs. TD, and between children who are good vs. poor readers. While these findings suggest that neural stability of sound processing may explain some degree of language variability both within and across different groups, detailed investigations into the relationships between ABR stability and specific components of higher-level language (e.g., syntax, lexicon) have not been performed. The current study aims to fill this gap by replicating Russo et al. (2009) with a more direct measure of ABR stability, and then examining relationships among ABR stability and detailed measures of language, including phonetic discrimination, lexical relations, and syntactic production.

1.3. *Phonetic Development: A pivot between the brainstem and higher order language?*

Thus far, ABR-language associations have primarily implicated phonetic processing, as observed relationships include early reading prowess, spelling, and phonological awareness. (Hornickel & Kraus, 2013; Neef, Schaadt, & Friederici, 2017). This link may be fairly direct: slower or less stable processing of the auditory signal at the brainstem may impact the integrity of the signal processing in the cortex, leading to poor sound representation. Indeed, more robust neural encoding of the stimulus acoustics by the brainstem has been reported to be associated with better speech sound categorization in adults (Bidelman, Weiss, Moreno, & Alain, 2014; Weiss & Bidelman, 2015); thus, high-fidelity neuroacoustic encoding may be a vital precursor to perceptual categorization of sound.

However, the findings linking ABRs to broad language measures hint at ‘downstream consequences’ of atypical ABRs for grammatical and lexical performance (Russo et al., 2009; Basu et al., 2010; Gabr & Darwish, 2016). For example, to consistently assign speech sounds to lexical or morphological targets, these sounds need to be categorized into sequences of phonological units, which is no small feat, as speech sounds vary along a continuum of small acoustic changes, and speech categorization requires ignoring some small variations of a sound in favor of hearing discrete classes of sounds (Liberman, Shankweiler, & Liberman, 1989; Pisoni & Luce, 1987). During phonological and phonetic development, representations of individual sounds are built up into a complex phonological system, which also facilitates speech perception and word learning by serving as a stable anchor for understanding. (Liberman et al., 1989; Archer & Curtin, 2016; Storkel, 2004).

Connections between phonological and lexical development are evident in findings that phonological difficulties impact word learning in the preschool years; for example, children with poor phonological skills (e.g., indexed by significant difficulties in production of word initial and word final consonant sounds not due to organic causes such as cleft palate or intellectual disability; Felsenfeld, Broen, & McGue, 1992). Difficulties in accurately repeating novel words, for example, have also been related to vocabulary acquisition, indicating that those children who have less well-developed phonological memory may struggle to retain the phonological forms of new words (Gathercole, Service, Hitch, Adams, & Martin, 1999). Preschoolers with delays in phonological production (e.g., consistent omission of consonant segments or clusters) also do not learn novel words as readily as TD peers, especially when the new words are phonologically similar to many other words the child already knows (Storkel, 2004; Storkel, Maekawa, & Hoover, 2010).

Furthermore, phonological and phonetic processing also aid in grammatical development; for example, efficiently segmenting and representing the grammatical morphemes that help child language learners to discover their language’s overall sentence structure (e.g., head-first vs. head-final; Gervain, Nespor, Mazuka, Horie, & Mehler, 2008), as well as to distinguish noun phrases from verb phrases (Mintz, Newport, & Bever, 2002; Gleitman & Wanner, 1982; Aslin & Newport, 2012; Demuth, 2015). Corroborating evidence comes from studies in which poor phonological encoding and/or underspecified representations are observed in children who have specific impairments in grammatical acquisition (see Archibald & Noonan, 2015, for a recent summary).

In sum, there is a substantial literature attesting that variability in ABRs are associated with variability in children’s phonetic representation and reading performance, and possibly also their broader language (Russo et al., 2009; Hornickel & Kraus, 2013; Neef, Schaadt, et al., 2017). There is a second substantial literature demonstrating that variability in children’s phonetic processing is associated with variability in their lexical and grammatical performance. One of our goals for this study is to connect these two literatures, and investigate how variability in ABRs, phonetic processing, and lexical and grammatical development, might all be related.

1.4. *Current study aims*

In sum, this study aims to fill three gaps, all of which focus on addressing how language variability relates to the stability of neural encoding of sound in the brainstem. First, although indices derived from ABR, including stability, have been found to predict various aspects of language (Hornickel & Kraus, 2013; Hornickel et al., 2009; Neef, Schaadt, et al., 2017; Russo et al., 2009; Skoe et al., 2017), a comparison of individual differences in ABR stability and concurrent language ability at multiple specific linguistic levels has not been undertaken. The current study investigates the relationships between subcortical processing of speech and concurrent language (phonetic, lexical, syntactic) ability in school age children to fill this gap. Following the Auditory Stability Hypothesis, children with more stable neural encoding of speech sounds are predicted to have better phonetic discrimination skills, as well as stronger lexical and syntactic performance. Second, the study will examine the intersection of these relationships, by testing whether the ability to discriminate between sounds mediates the relationship between early sensory processing and lexical and grammatical processes. Third, we include a sample of children with ASD to investigate whether ABR stability and/or latency distinguish them from their TD peers. Following Tomblin (2015), though, we also hypothesize that the nature of the relationship between stability and language performance will be fundamentally similar in both TD and ASD children, although more variability in the ASD group is expected (Kjelgaard & Tager-Flusberg, 2001; Russo et al., 2009; Swensen, Kelley, Fein, & Naigles, 2007; Wittke, Mastergeorge, Ozonoff, Rogers, & Naigles, 2017).

In pilot work for this study, we have documented relationships between /da/ neural stability at school age and children's *earlier* language ability. That is, ABRs to /da/ were collected from both TD school aged children and school aged children with ASD, and their neural response stability was compared with the children's spontaneous speech from language samples collected when they were preschoolers. Children who as preschoolers had produced a higher proportion of nouns and plural markers on nouns, as well as more progressive morphemes (*-ing*) and auxiliaries with their verbs, manifested more stable neural responses to /da/ several years later (Jones et al., 2017; Meagher et al., 2017). While these findings are promising, the time differential between the neural and behavioral tests makes interpretations of these relationships somewhat complicated. Thus, relationships between neural stability and multiple components of concurrent language performance are the target of the current study.

2. Materials and methods

2.1. Participants

Thirteen children with ASD (1 female) and fifteen TD children (2 females), all monolingual English speakers, participated in the current study as part of an ongoing longitudinal investigation of language development in autism (Naigles & Fein, 2017). Inclusionary criteria for the current study consisted of passing a three-part hearing screening: a 20 dB HL pure tone audiometric peripheral hearing test at 500, 1000, 2000, 4000, and 8000 Hz; normal outer and middle ear status confirmed by otoscopy; and normal outer hair cell function as confirmed by distortion product otoacoustic emissions. Four children (all boys, one with ASD) participated in the ABR portion of the study but did not complete the phonetic discrimination task or language assessments, leaving a final sample of twelve children with ASD and twelve TD children.

Participants with ASD were originally recruited as toddlers through various service providers in the Northeastern U.S. and all had received a diagnosis of autism prior to being contacted regarding participation in the original study. At the initial visit and some subsequent visits, the Autism Diagnostic Observation Schedule-Generic (ADOS-G; Lord et al., 2000) was used to confirm the diagnosis. Children in the TD group were originally recruited from the local area via birth announcements and word of mouth. The TD and ASD groups for each of the three cohorts of the longitudinal study were initially matched on language level, resulting in the ASD groups being chronologically older than the TD groups at the first visit. This is reflected in our sample, which draws from each of the three cohorts. For our subset of children, their ages, ADOS scores, vocabulary, and cognitive scores at the initial visit are found in Table 1.

At the time of the current study, because only a subset of the original families participated in follow-up testing, the TD and ASD groups were not statistically different with regard to age as indicated by a Welch's t-test (which does not require that population variance is equivalent [$t(1, 18.79) = 2.55$, $p = .127$]); however, the age distributions of the two groups differed, as noted by the larger standard deviation in the ASD group (and see Fig. 1). A Shapiro-Wilk test indicated that while the ASD age distribution was within the normal bounds, ($W(12) = 0.934, p = .423$), the TD group showed a significant departure from normality, ($W(12) = 0.796, p = .009$). The distribution of ages shows that the members of the TD group are more similar in age, with the ASD group including both more younger members and more members over 13 years of age. Language development trajectories were also different for the two groups during the time period between the initial visit and the current visit, resulting in the TD group showing more age-appropriate language performance, as reflected by their standard scores on a battery of language tests, than the ASD group at the time of the current study (see also Fusaroli et al., 2019). Standard scores calibrated to the participants' age revealed significant group differences for all of the four subtests. While standard scores reflect language performance with respect to age-level expectation, raw performance scores provide an index of actual performance, and when these were compared no significant group differences were found on any of the language subtests, indicating that the groups performed similarly overall. Group level differences emerged for only one subtest of the nonverbal cognitive subtests. Participants' concurrent ages, language performance, nonverbal IQ, and ADOS-2 scores (Lord et al., 2012) scores can be found in Table 2.

2.2. Stimuli and procedure

2.2.1. Standardized measures

Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord et al., 2012). The ADOS was administered to verify the current level of autism characteristics. Module 3 was administered to all children. Two children (one TD, one ASD) did not receive the ADOS-2 during the current visit due to time constraints.

Clinical Evaluation of Language Fundamentals, Fifth Edition (CELF-5; Wiig & Secord, 2013). The CELF-5 was administered to assess current language performance. Four subtests were given (Word Classes, Repeating Sentences, Formulated Sentences, and Following Directions) as baseline language measures to characterize TD and ASD groups (see Table 2); however, only two of these (Word Classes, Formulated Sentences) were included in the ABR-language investigation because these most directly cover lexical and grammatical abilities. The Word Classes subtest evaluates understanding of meaning-based relationships between words; for example, four words are presented (e.g., *knife, skillet, fork, lamp*) and the child is asked which two go together best. In the above example, only the 'knife, fork' pair would receive points. Relations such as synonyms, antonyms, and part-whole are probed. The Formulated Sentences subtest evaluates the formation of grammatically correct spoken sentences based on a picture and word prompt. For example, a picture showing a child looking under the porch of a house could be paired with 'where', such that a possible sentence could be 'That girl is trying to find where her dog went'. Points are allotted for word use and relevance to the picture, but also docked for *each* grammatical error. Thus, Word Classes serves as our measure of lexical performance and Formulated Sentences serves as our measure of grammatical performance.

Differential Ability Scales (DAS; Elliot, 1990). The DAS was administered to gauge children's general level of nonverbal cognitive functioning. Three subtests were administered: Matrices, Recall of Digits, and Pattern Construction.

2.2.2. Electrophysiological measures

Using well-established protocols, ABRs were recorded to two stimuli: a 100-microsecond click stimulus (31.1/sec) and a 40-millisecond (ms) synthesized speech stimulus /da/ (10.9/sec) (Hornickel & Kraus, 2013; Banai et al., 2009). The /da/ stimulus was produced in KLATT (Klatt, 1980) and its fundamental frequency (F0) rose from 103 to 125 Hz with voicing beginning at 5 ms and an onset noise burst during the first 10 ms; this stimulus has been utilized in previous investigations of ABR-language connections (Banai et al., 2009; Skoe et al., 2017). Three Ag/AgCl plated electrodes were placed on the head using a vertical, ipsilateral montage (Cz, right ear, forehead). To achieve a low-impedance recording (< 5kOhms), electrode sites were cleansed with a gentle scrub and adhered using conductive paste.

The speech and click stimuli were presented in separate blocks at

Table 1
Characteristics of children in the Typically Developing (TD) and Autism Spectrum Disorder (ASD) groups at visit 1 (initial recruitment).

	TD M(SD) range	ASD M(SD) range	F	p	η_p^2
Age (months)	19.90 (1.20) 19.03–23.3	30.93 (5.87) 18.77–41	37.81	<**0.001**	0.643
ADOS	0.83(1.34) 0–4	12.67(3.65) 7–18	111.1	<**0.001**	0.835
CDI Understands and Says	122.67(113.1) 11–317	116.50(116.69) 7–328	0.017	0.897	0.001
Mean Length Utterance	1.44(0.26) 1–1.86	1.87(0.89) 1–3.58	2.64	0.119	0.107
MSEL					
Fine Motor	22.25(2.53) 19–28	25.00(3.81) 20–32	4.34	**0.049**	0.165
Expressive Language	20.17(4.15) 15–28	21.0(7.35) 12–33	0.117	0.763	0.005
Receptive Language	25.0(3.22) 20–31	24.92(7.79) 12–36	0.001	0.973	<0.001
Visual Receptive	26.33(3.06) 21–30	26.67(6.51) 12–34	0.026	0.874	0.001

ADOS, Autism Diagnostic Observation Schedule; CDI, MacArthur-Bates Communicative Development Inventory; MSEL, Mullen Scales of Early Learning.

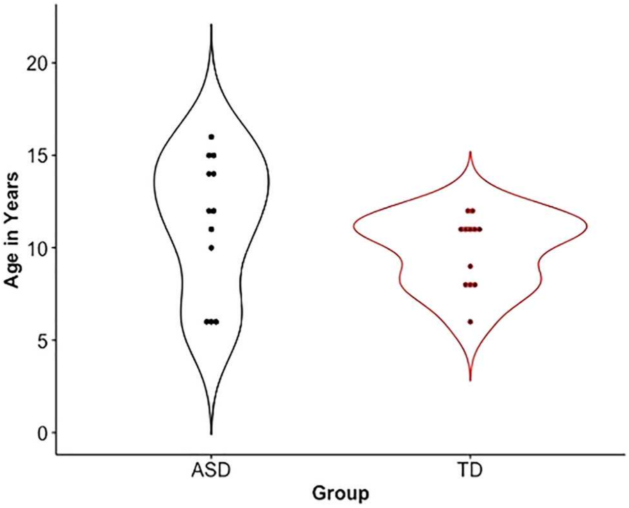

Fig. 1. Violin plot depicting the age distributions of ASD and TD group.

80 dB SPL into the right ear through an insert earphone (ER-3A, Etymotic Research, Inc). To minimize stimulus artifacts, stimuli were presented in alternating polarity, with responses to the two polarities averaged (Skoe & Kraus, 2010; Chimento and Schreiner, 1990). The Navigator Pro AEP system (Natus Medical, Inc.), a portable laptop ERP system, controlled both stimulus delivery and ERP averaging. For the /da/ stimulus, the response was bandpass filtered online from 100 to 2000 Hz, with a recording window that began 15 ms prior to the stimulus onset and extended 20 ms post stimulus offset. Stability was calculated over the response window from 19.5 to 44.2 ms (Skoe et al., 2015). For the click stimulus, the averaging window extended from 0 to 10 ms. Stability was calulated over the click response window of 0 to 8 ms. Trials exceeding ± 23.8 μVolts (i.e., muscle artifacts) were automatically excluded from the average. For the click stimulus, 1000 sweeps were averaged and for the /da/ stimulus 3000 sweeps were averaged, both online. This process was repeated for each stimulus to create two sub-averages per stimulus that were manually combined offline to generate averages that represented 2000 sweeps of the click stimulus and 6000 sweeps of the /da/ stimulus. The AEP software saves the recordings as averages; individual sweeps or subsets of sweeps cannot be retrieved from the saved recordings.

We calculated four specific variables of interest at the group level: latency of Wave V for clicks; latency of Wave V for /da/; click stability; and /da/ stability. Wave V is the most robust component found in a human ABR, and is thought to originate primarily from electrical activity in the inferior colliculus (Hall, 2006). Extracellular recordings from the inferior colliculus suggest that neural stability measured from scalp electrodes reflects trial-by-trial variation within this subcortical auditory structure (White-Schwoch, et al., 2017). The Wave V peak of the click response and the response to /da/ were manually identified and a second experienced observer confirmed identification. Neural stability was calculated in accordance with standard practice for this stimulus (Hornickel & Kraus, 2013, Skoe et al., 2015). The neural stability of the auditory brainstem response was determined by the linear relationship the two subaverage waveforms, with correlation coefficient r values closer to 1 representing more morphologically similar waveforms. Given that the sampling distribution of correlation coefficients is not normally distributed, a Fisher z-transformation was applied to neural stability correlation coefficients ($z' = 0.5 *\ln(1 + r/1 - r)$) to normalize the distribution. The Fisher z-transformation scores (z') were used in the analyses.

2.2.3. Phonetic discrimination task

The discrimination task stimuli were pairs of novel bisyllabic CVC-CVC (consonant vowel consonant) novel words that differed by only one phonetic unit (e.g., *kulkeet* vs. *tulkeet*), or were identical (e.g., *kulkeet* vs. *kulkeet*). To create the stimulus list, CVCs were taken from a list of CVC-CVCs in Luce and Pisoni (1998). The sound sequences of the novel words conformed to English phonology, and thus all pairs were possible words in English. The words were recorded in a soundproof booth by an adult female native speaker of American English and concatenated in Praat (Boersma, 2001) so that each pair had 500 ms of silence between words. Eighty pairs were presented, half of which were identical, and the other half differed by one sound in the initial consonant. In all cases the differing sound varied on place of articulation. Trials within each block were randomized across participants and coded for accuracy and reaction times.

The phonetic discrimination task was presented using PsychoPy (Peirce, 2007). Children heard pairs of novel words presented through headphones at a comfortable listening level while seated opposite a laptop with a large button box holding one red and one green button. Children were asked to press the green button if they considered the two novel words to be identical and the red button if they determined them to be different words. Reaction times and accuracy were recorded by the computer.

A training phase was conducted immediately prior to testing. To introduce children to the discrimination task, four pairs of pictures (dogs, cats, rabbits, and birds) were presented sequentially and the child was asked to press the green button if they were the same and the

Table 2
Characteristics of TD and ASD groups at time of current study.

	TD *M(SD)* Range	ASD *M(SD)* Range	Welch's *t*	*p*	Cohen's' *d*
Age (years)	10.50(2.15) 7–13	12.33(3.34) 7–17	2.56	0.127	0.1
ADOS-2	1.45(2.33) 0–6	9.55(4.41) 3–17	28.867	< **0.001**	0.591
CELF 5 Raw Scores					
Formulated Sentences	37.50(8.43) 21–47	29.42(13.35) 7–46	3.15	0.092	0.72
Word Classes	31.50(5.14) 22–38	27.42(7.01) 15–35	2.65	0.119	0.66
Repeated Sentences	58.42(11.19) 41–77	45.67(20.81) 12–71	3.5	0.079	0.76
Following Directions	25.58(6.43) 10–32	21.33(7.52) 9–32	2.21	0.151	0.59
CELF 5 Standard Scores					
Formulated Sentences	10.67(2.42) 7–15	6.92(3.75) 1–14	8.45	**0.009**	1.19
Word Classes	12.50(2.88) 10–19	8.42(2.78) 2–12	12.51	**0.002**	1.44
Repeated Sentences	11.92(3.14) 6–19	7.7(3.65) 1–13	9.33	**0.006**	1.24
Following Directions	11.75(2.8) 7–17	8.67(3.94) 3–15	4.89	**0.039**	0.90
DAS Raw Scores					
Pattern Construction	46.67(6.23) 34–52	35.83(12.71) 17–52	7.03	**0.017**	1.08
Recall of Digits	21.42(4.1) 14–29	20.75(5.63) 11–30	0.110	0.744	0.14
Matrices	20.17(5.92) 11–32	15.83(8.76) 2–32	2.02	0.172	0.58
Composite	88.25(13.29) 66–105	72.42(25.33) 31–112	3.68	0.073	0.78

ADOS 2, Autism Diagnostic Observation Schedule; CELF 5, Clinical Evaluation of Language Fundamentals, Fifth edition; DAS, Differential Ability Scales

red button if they were different pictures. The children were given feedback on their responses and advised about any incorrect answers during training.

Phonetic discrimination was introduced through four auditory training pairs, which were CVC-CVCs similar to test items but did not include any of the CVCs used in the test phase (e.g., *zainbert* and *zainbert*). Two same and two different pairs were presented with directions identical to those of the picture training. A trial ended when the child pushed a button.

2.3. Procedure

The protocol was approved by the Institutional Review Board of the University of Connecticut. All assessments, including the ABRs, were conducted in the children's homes, usually in a living room or family room. Parents were allowed to be present during testing but were asked to refrain from participating in any way. Assessments were conducted over the course of two visits, which were on average six months apart (range 0–14 months). ABRs were collected during the first visit, and phonetic discrimination, nonverbal cognition, language performance, and diagnosis were assessed at the second visit.

Prior to both ABR and behavioral testing, parents gave written consent and participants provided written assent prior to the behavioral testing. All children were able to indicate via writing that they were willing to participate. Hearing screenings were conducted immediately prior to ABR collection. ABR collection took between 30 and 45 min including the electrode application time, with breaks as needed. During the recordings, participants sat comfortably on a couch or chair while watching a movie on a laptop computer/tablet at a low volume. This facilitates sitting still during testing, and the low volume has been found to not interfere with ABR recording (Russo et al., 2009, Hornickel & Kraus, 2013). At the second visit the phonetic discrimination task was administered first, followed by the DAS, the CELF 5, and the ADOS 2. Breaks were given as needed and the visit averaged 2.5 h in length.

2.4. Analysis

ABR data analysis was performed following published reports using similar stimulus and recording parameters (Banai, Zecker, & Kraus, 2005; Hornickel & Kraus, 2013; Russo, Nicol, Musacchia, & Kraus, 2004). All ABR data analysis was automated using routines coded in MATLAB 7 (The MathWorks, Inc., Natick, MA). All statistical analysis was performed in SPSS (SPSS Inc., Chicago, IL). Analysis of variance tests (ANOVA) were used to determine the degree of group level differences in the electrophysiological and phonetic discrimination measures. Nonverbal cognition will not be used as a control variable for group level differences as the groups only differed significantly on one subtest. Welch's t-tests were used as they do not require equal variance between groups. Shapiro-Wilk tests indicated overall distribution normality; only the Formulated Sentences scores for the TD group and entire sample, and phonetic discrimination scores for the whole sample, were not normally distributed. Table 3 shows the distribution normality results.

Relationships between the ABR neural stability measures and language performance (CELF Formulated Sentences and Word Classes, phonetic discrimination) were investigated using Pearson's product-moment correlation coefficients. All analyses were performed for the entire sample as well as for the TD and ASD groups separately. Given that we expected to replicate previous findings showing significant relationships between ABR and CELF scores, a series of regression analyses was performed to determine whether phonetic discrimination mediates the relationship between /da/ stability and concurrent language (Russo et al., 2009). Due to small numbers of participants the regression was performed on the full sample.

Table 3
Shapiro-Wilk tests for normality of distribution.

	W	df	*P*
Click Wave V Latency			
TD	0.924	12	0.318
ASD	0.943	12	0.539
ALL	0.980	24	0.897
/da/ Wave V Latency			
TD	0.897	12	0.146
ASD	0.928	12	0.363
ALL	0.957	24	0.380
Click Stability			
TD	0.934	12	0.419
ASD	0.910	12	0.212
ALL	0.974	24	0.769
/da/ Stability			
TD	0.927	12	0.347
ASD	0.959	12	0.762
ALL	0.988	24	.991
Phonetic discrimination			
TD	0.926	12	0.339
ASD	0.881	12	0.09
ALL	0.845	24	**0.002**
CELF Formulated Sentences			
TD	0.852	12	0.039
ASD	0.901	12	0.164
ALL	0.875	24	**0.007**
CELF Word Classes			
TD	0.922	12	0.3
ASD	0.896	12	0.143
ALL	0.921	24	0.061

3. Results

Results are first presented for group level differences; electrophysiological results will be reported first, followed by the behavioral results. Then, correlational analyses are presented to examine the relationship between variables on the individual level both with and without respect to diagnosis. Results are organized around three central questions. First, how do the groups differ on the ABR measures? Second, to what degree does one of the ABR measures, neural response stability for speech, correlate with language performance: phonetic discrimination, CELF Formulated Sentences, Word Classes? Third, given that some relationships are found, does phonetic discrimination mediate between neural stability and CELF-based language performance?

3.1. Group level differences

3.1.1. Electrophysiological measures

Results for ABR comparisons can be found in Table 4. A significant group difference was found for click Wave V latency, with the TD group having shorter latencies than the ASD group. No significant between-group differences were found for /da/ wave V latency, click neural stability, or /da/ neural stability, although the means for click and /da/ Wave V latency and /da/ neural stability are in the predicted directions of the ASD group having longer latencies and less stable responses. The larger standard deviations for the ASD group for /da/ neural stability (0.21 compared to 0.15 for the TD group), suggests differences in the distribution of neural stability responses across groups, and Fig. 2 depicts the group distributions for the /da/ z' scores. Furthermore, when individual /da/ neural stability values were compared to age relevant norms (Skoe et al., 2015), five of the 12 children with ASD fell outside of age-related norms (+/- 1 SD) while only one TD child did. Thus, nearly half of the ASD group did not have age-appropriate stability scores. As only neural stability for the speech stimulus was of interest, no analyses comparing click neural stability to language outcomes were performed.Table 5.

Table 4
ABR results for TD and ASD Groups.

	TD *M(SD)*	ASD *M(SD)*	Welch's *t*	*p*	Cohen's *d*
Click Wave V Latency (ms)	5.60(0.17)	5.75(0.16)	5.21	**0.033**	0.91
/da/ Wave V Latency (ms)	6.45(0.24)	6.55(0.22)	1.10	0.306	0.43
Click Stability z' scores	1.21(0.28)	1.27(0.48)	0.14	0.711	0.15
/da/ Stability z' scores	1.06(0.29)	1.04(0.48)	0.010	0.923	0.050

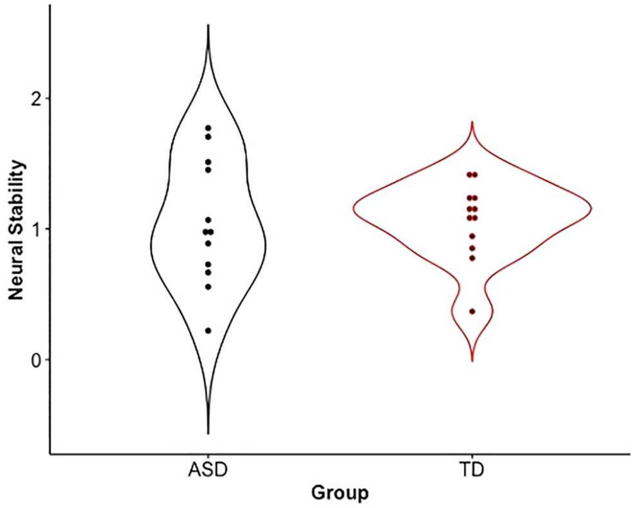

Fig. 2. Violin plot of /da/ neural stability z' score distributions of ASD and TD groups.

3.1.2. Phonetic discrimination

Both TD ($M = 73.17$, $SD = 4.22$) and ASD ($M = 66.08$, $SD = 11.07$) groups performed significantly above chance on the phonetic discrimination task (chance estimated at 40/80). The TD group provided on average more correct responses than the ASD group; although the difference did not meet statistical significance, the effect size was large (Welch's $t(1, 14.13) = 4.29$, $p = 0.057$; Cohen's $d = 0.846$). The TD group was also faster to respond on correct trials ($M = 4.82$ s, $SD = 0.27$) than the ASD group ($M = 5.17$ s, $SD = 0.56$); again, the difference was not statistically significant but the effect size was large (Welch's $t(1, 16.01) = 3.96$, $p = 0.064$; Cohen's $d = 0.796$).

3.2. Individual differences

3.2.1. Relationships between neural response stability and language performance

Pearson's product-moment correlation coefficients were computed to assess the relationship between neural stability and phonetic discrimination performance. Statistically significant positive correlations were found for the entire group ($r = 0.478$, $n = 24$, $p = .018$) and ASD group alone ($r = 0.575$, $n = 12$, $p <= .05$). While the relationship for the TD group alone was not statistically significant ($r = 0.293$, $n = 12$, $p = .355$), the correlation was in the expected direction. When age and DAS composite were included as covariates, the relationships for the entire group ($r = 0.502$, $n = 24$, $p = .017$) and the ASD group ($r = 0.652$, $n = 12$, $p = .041$) remained, and the relationship for the TD group still did not reach statistical significance ($r = 0.203$, $n = 12$, $p = .575$). No significant interaction was found between group status and neural stability on phonetic discrimination performance, $b = 0.702$, $t(20) = 1.024$, $p = .318$. Fig. 3a depicts the relationship between neural stability z' scores and results from the phonetic discrimination task.

Table 5
Correlations between CELF 5 Raw Scores and Neural Stability z' scores for the entire sample, and for TD and ASD groups separately.

	ALL	TD	ASD	ALL	TD	ASD
	Raw Scores			Controlling for DAS and Age		
Formulated Sentences	0.518**	0.356	0.619*	0.585*	0.434	0.697*
Word Classes	0.343	0.135	0.457	0.320	−0.010	0.566†
	Log transformed data					
Formulated Sentences	−0.469**	−0.347	−0.604*			

Note
† p < .1.
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Correlational analyses were also performed to assess the relationship between neural stability and the CELF measures of syntax and semantics. No relationship emerged between raw scores for CELF Word Classes and neural stability for either group when examined separately or as a whole. However, significant positive correlations were found between raw scores for CELF Formulated Sentences and neural stability for the entire group, indicating children with more stable neural responses showed better syntactic performance. Analyzing each group separately revealed a significant correlation for the ASD group, but not the TD group. When age and DAS composite were entered as covariates the relationships between neural stability and syntactic performance remained. The relationship also held when log transformed data was used (the correction now negative as the syntactic performance data was left skewed and had to be reversed prior to the natural log transform). Correlations between neural stability scores and CELF raw scores can be found in Table 4. Fig. 3 depicts the relationship between /da/ neural stability scores and Formulated Sentences (3b) and Word Classes (3c) raw scores.

3.2.2. Phonetic discrimination and its relationship to syntactic and lexical performance

Correlations between phonetic discrimination performance and Formulated Sentences and Word Classes scores can be found in Table 6. Statistically significant positive correlations were found for the entire group between phonetic discrimination and both CELF scores; Formulated Sentences correlated significantly with phonetic discrimination within both the ASD and TD groups whereas Word Classes only correlated significantly with phonetic discrimination within the ASD group. Table 6 shows that these relationships are generally maintained when age and DAS composite are entered as covariates. Fig. 4a depicts the relationship between phonetic discrimination and Formulated Sentences and Fig. 4b depicts the relationship between phonetic discrimination and Word Classes.

3.2.3. Mediation analysis

Multiple regression analyses were conducted to assess individual components of the proposed mediation model. Because phonetic

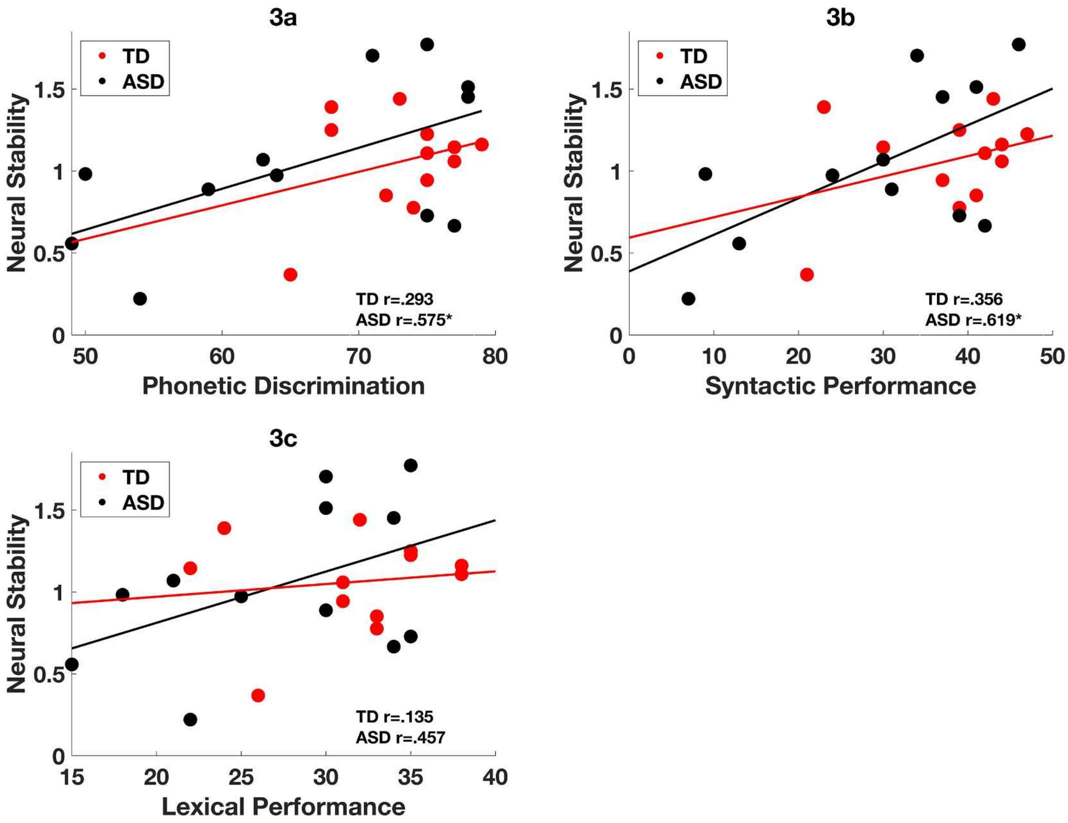

Fig. 3. Relationships between /da/ neural stability z' scores and language: 3a depicts the relationship between neural stability and phonetic discrimination by groups; 3b depicts the relationship between neural stability and syntactic performance (Formulated Sentences raw scores) by groups; and 3c depicts the relationship between neural stability and lexical performance (Word Classes raw scores) for both groups.

Table 6
Correlations between Phonetic Discrimination and CELF 5 Raw Scores for the entire group and for the TD and ASD groups separately.

	ALL	TD	ASD	ALL	TD	ASD
	Raw Scores			Controlling for DAS and Age		
Formulated Sentences	0.874**	0.657*	0.923**	0.668**	0.283	0.869**
Word Classes	0.778**	0.344	0.896**	0.370	−0.432	0.718*
	Log transformed data					
Formulated Sentences	0.660**	0.450	0.774**			

Note
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

discrimination and Formulated Sentences scores were not normally distributed, the mediation analysis was conducted after flipping the left skewed data and performing a natural log transform to normalize them. Our mediation analysis tests a possible causal chain in which ABR neural stability affects phonetic discrimination which in turn impacts syntactic performance. Following a simple Baron and Kenny (1986) model we performed a series of regressions: neural stability predicting syntactic performance (c-path); neural stability predicting phonetic discrimination (a-path); phonetic discrimination predicting syntactic performance (b-path); and neural stability and phonetic discrimination predicting syntactic performance (c'-path with respect to neural stability).

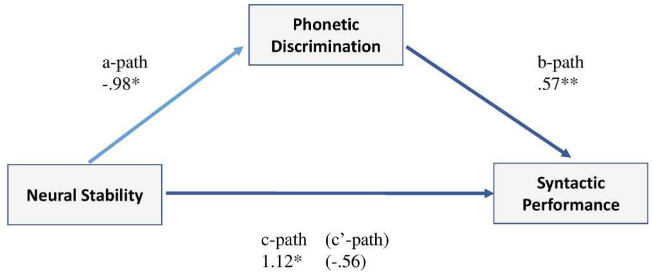

Fig. 5. Phonological Discrimination Mediates the Relationship between /da/ Neural Stability and Syntactic Performance. Neural stability predicts phonetic discrimination and phonetic discrimination predicts formulated sentences, as seen by the a and b paths respectively. The total effect of neural stability on Formulated Sentences is represented by the c-path. The direct effect, represented by the c'-path is not significant.

As depicted in Fig. 5, the regression analyses found that /da/ neural stability scores were positively associated with Formulated Sentences scores (i.e., c-path; b = 1.12, *t* (22) = 2.4, *p* = .021) and with phonetic discrimination (i.e., a-path; (b =- 0.98, *t* (22) = 2.1, *p* = .044). Moreover, the mediator, phonetic discrimination, was positively associated with Formulated Sentences (i.e., b-path; (b = 0.57, *t* (22) = 3.26, *p* = .003). In addition, results indicated that the direct effect of /da/ neural stability on Formulated Sentences became non-significant when controlling for phonetic discrimination (i.e., c'-path), thus suggesting full mediation (b = −0.56, *t* (22) = 1.3, *p* = .186). As both the a-path and b-path were significant, the indirect effect, a metric of how syntactic performance would change if neural stability was held constant and phonetic discrimination was changed as it would based on one unit changes in neural stability, was tested using a bootstrap estimation approach with 5000 samples (Preacher & Hayes, 2004). Results indicated the indirect effect was significant (effect = −0.56, SE = 0.23, 95% CI = −1.03 to −0.09), confirming the mediation role of phonetic discrimination.

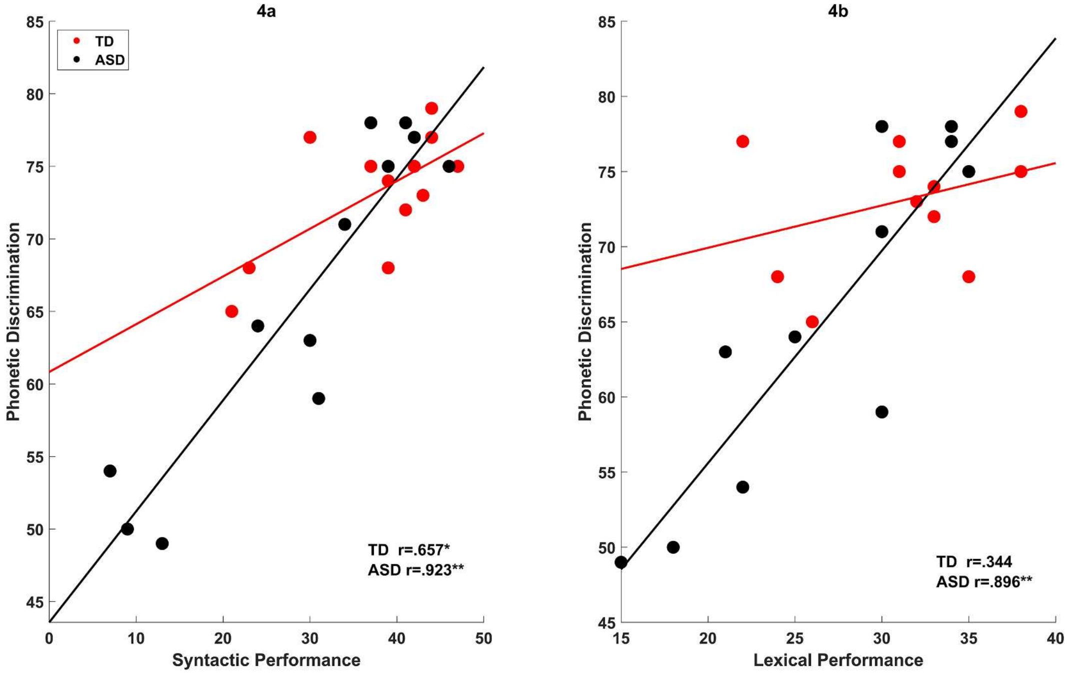

Fig. 4. Relationship between phonetic discrimination scores and syntactic and lexical performance for TD and ASD groups. 4a depicts phonetic discrimination scores and syntactic performance (Formulated Sentences raw scores); 4b depicts phonetic discrimination scores and lexical performance (Word Classes raw scores).

4. Discussion

The goal of this study was to investigate how language variability in school-aged children related to their stability of neural encoding of sound in the brainstem. We included a sample of children with ASD to extend the range of both neural and language performance, and to further investigate whether ABR latency and/or stability distinguishes them from their TD peers. We also examined relationships between individual differences in ABR stability and concurrent language ability at multiple levels, with the hypothesis that the ability to discriminate between sounds mediates the relationship between early sensory processing and lexical and syntactic performance. Differences between the TD and ASD groups were observed in ABRs to click-evoked Wave V latency but not to the other ABR measures. Furthermore, neural stability was related to phonetic and syntactic but not lexical performance, and phonetic discrimination mediated the relationship between neural stability and syntax. In what follows, we discuss these findings with respect to our hypotheses.

4.1. Group level differences in ABRs

Our first findings were at the group level. The TD group had a significantly shorter click Wave V latency than the ASD group; this effect was in line with the majority of findings in the literature (see Miron, Beam, & Kohane, 2018 for an overview). However, we found no significant group differences for neural stability for the /da/, neural stability for the click, or for /da/ Wave V latency, although the ASD group's /da/ wave V latency was numerically slower than that of the TD group. The absence of a group difference for /da/ Wave V latency was unexpected, especially because speech ABRs are considered more sensitive measures of auditory processing than click ABRs (Song, Banai, Russo, & Kraus, 2006). Further investigation of the data, though, revealed that one TD participant had an unusually short click Wave V latency in comparison to his /da/ Wave V latency, enabling a group difference in click Wave V but not /da/ Wave V latency. Thus, any interpretations of the click Wave V latency group level difference without a corresponding /da/ Wave V latency group level difference must be made cautiously.

The absence of group differences for /da/ neural stability also runs counter to Otto-Meyer and colleagues' (2017) report that ABR stability across several stimuli was lower among children with ASD than TD peers; however, the broader age range of our study sample may explain the discrepant results. Participants in both the TD and ASD groups in the Otto-Meyer study ranged in age from 7 to 13 years, while the participants in this study spanned 7 to 17 years. Given the continual maturation of the subcortical auditory system into late adolescence (Skoe et al., 2015; Krizman et al., 2015), fine scale group differences may be more difficult to observe when using broader age ranges (Skoe et al., 2015). Despite this limitation, the direction of the relationship (of /da/ responses being less stable in the ASD than TD groups) was in line with the previous literature. The ASD group also had more variability in their neural stability, with five of the 13 falling out of range of age-established norms (Skoe et al., 2013). Most interestingly, a potential bimodal distribution could be emerging for individuals with ASD in this study, as the very low and very high stability ends of the continuum were both populated by children with ASD, with the TD children falling mostly in the middle (see Fig. 2).

4.2. Main Findings: Individual differences reveal ABR-Language relationships

Our primary findings address the question of individual differences, specifically whether neural stability related to language at any of the levels of phonology/phonetics, lexicon, and/or syntax. Our results provide strong evidence for the Auditory Stability Hypothesis, which predicted that children with more stable neural encoding of speech sounds would demonstrate better language performance. In particular, variability in /da/ neural stability related to variability in ability to phonetically discriminate nonwords, as children with ASD and TD who had more stable encoding performed better on our phonetic discrimination task. These findings accord with the established relationship between reading and ABR (Hornickel & Kraus, 2013; Skoe et al., 2017) with phonology being the putative link. These findings also provide corroboration that the stability of subcortical neural encoding of speech is varied across individuals and that individual differences can relate to meaningful differences in how speech sounds are categorized, potentially by influencing the formation of stable mental representation of sound.

Results further showed that syntactic performance and /da/ stability were also related, indicating that more robust brainstem encoding of speech may facilitate more accurate syntactic productions. This finding supports our hypothesis that poor neural stability may decrease representational acuity in the short-term, and/or increase attentional or processing demands, which in turn hinder young learners from developing and refining syntactic knowledge. This is in line with findings that children with grammatical impairments also have poor phonological encoding and/or underspecified phonological representations (Archibald & Noonan, 2015). The success of grammatical acquisition rests partially on noticing small differences in morphemes that are often unstressed, as well as in organizing these morphemes into larger structural frames (e.g., distributional learning; Gleitman & Wanner, 1982; Mintz et al., 2002). Better ability to discriminate between sounds appears to allow these processes to proceed more efficiently.

Finally, phonetic discrimination mediated the relationship between neural stability and syntactic performance combining across groups. Thus, consistent with the Auditory Stability Hypothesis, our findings suggest that unstable subcortical encoding of sound may cascade into difficulties in macro level language abilities. We leverage previous work into the neural mechanisms to posit that instability can occur at the level of the single trial (White-Schwoch, et al., 2017) which extrapolated to the real world sets up the possibility that children with low neural stability encode speech sounds subtly differently each time the same phonetic token is encountered, leading to fuzzy phonological representations. These findings begin to fill in the gap between neural encoding of sound and macro level language, with phonetics as an important intermediary step. Phonology and phonetic knowledge have previously been named as the connector between ABR stability and reading (Hornickel & Kraus, 2013); we now further support its importance as a connector to syntactic performance. That is, highlighting a link between ABR neural stability and syntax in which phonology plays an intermediary role is valuable as it illuminates the broader range of language functioning implicated in the downstream effects of how sound is processed in the brainstem. Variability in ABR response stability appears to be consequential for syntactic performance during middle childhood (the ages of our participants in this study), and so may be a significant contributor to the language learning difficulties that many children with ASD experience (Naigles & Chin, 2015).

No statistically significant relationships emerged between /da/ stability and lexical performance. However, the relationships for the entire group, as well as the TD and ASD groups individually, were positive; that is, all yielded correlation coefficients of 0.36 or greater. We conjecture that the small sample size might have left the study too underpowered to detect a significant relationship, especially with a measure that may not have provided a sensitive test of lexical knowledge. That is, the Word Classes subtest examined children's abilities to see connections between words in interesting ways (e.g., synonyms, antonyms, and semantic features such as shared characteristics, associations, or function); in effect, however, the number of questions contributing to variability was quite small; 93% of the children answered the first 24 questions correctly and only 17% were able to answer the final four questions, leaving only 13 questions (out of a total of 40) whose accuracy served to differentiate the sample. We were likely testing specific knowledge of only a few words rather than more general contours of semantic ability. Further support for this lack of variability can be seen in the standard deviations of Word Classes (*SD* = 6.3) which was half that of Formulated Sentences (*SD* = 11.67). While a small set of questions that rapidly increase in difficulty is important for quickly distinguishing typical from atypical lexicons, it may fail to provide the fine-grained differentiation needed for revealing individual differences. Assessments targeted at deeper vocabulary knowledge, such as the Peabody Picture Vocabulary Test (Dunn & Dunn, 2007), may be a better index. Furthermore, the ASD group showed a definite trend towards /da/ stability influencing lexical performance, especially when age was taken into consideration (see Fig. 3b).

5. Limitations and future directions

The results in this study have provided support for the Auditory Stability Hypothesis; however, there are of course some study limitations as well as future directions for testing this hypothesis. Our method for calculating neural response consistency from successive recordings within a session, and not interleaved or random sets of trials, is a potential limitation. It weakens our ability to directly tie our findings to trial-by-trial phenomenon, leaving open the possibility that reduced neural stability reflects neural adaption occurring over the course of the session or ordering effects, rather than trial-by-trial variation. Our interpretation, therefore, rests on previous findings. Other limitations of this study included its relatively low power, as well as evaluating a sample that may have been both too heterogeneous and not heterogeneous enough. Given the small sample size, the large age range of the ASD group likely limited the emergence of some group differences. At the same time, the smaller sensitivity of the lexical measure may have hampered the emergence of significant ABR-lexical relationships. Finally, given that roughly 15%-30% of individuals with ASD are nonverbal, many with few or no demonstrable language skills (Pickett, Pullara, O'Grady, & Gordon, 2009), this study in no way spanned the breadth of the ASD spectrum, impacting both group differences and possibly the ABR-language relationships.

The results of this study thus invite further study in several directions. First, a more robust look at lexical abilities, including vocabulary and categorization tasks, should be investigated with respect to auditory sensory processing, to ascertain a fuller picture of the downstream effects of neural stability. Second, the relationships between brainstem encoding of speech and syntax, lexicon, and phonetics/phonology should be examined in younger preliterate children. All of the children in this study had learned to read, which is a skill that displaces auditory processing as the sole driver of language development. The Auditory Stability Hypotheses needs to be tested at a developmental stage prior to reading to be able to see the extent to which children rely on neural encoding when they have not learned compensatory skills.

6. Conclusions

In conclusion, stable neural encoding of speech by the brainstem is associated with better language performance at both phonetic/phonological and syntactic levels in both TD and ASD school age populations. Furthermore, phonetic discrimination has been found to mediate the relationship between encoding stability of speech and syntactic performance. These findings corroborate the growing body of literature investigating subcortical contributions to language, and so provide strong support for the Auditory Stability Hypothesis (Banai et al., 2009; Hornickel & Kraus, 2013; Skoe et al., 2017; Neef, Müller, et al., 2017). These findings also suggest that children with ASD and TD children manifest similar developmental patterns with respect to the stability of encoding of speech by the brainstem, supporting the contention of Tomblin (2015) that children with language impairments may instantiate one end of the same developmental continuum as TD children.

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