5-6-2017

Effects of Language and Reading Ability on Input-Driven Plasticity of Phonetic Category Structure

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B.A., University of Connecticut, 2015

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Arts

At the

University of Connecticut

2017

APPROVAL PAGE

Master of Arts Thesis

Effects of Language and Reading Ability on Input-Driven Plasticity of Phonetic Category Structure

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2017

Acknowledgments

First, I thank Dr. Rachel M. Theodore for her invaluable instruction and support. I also thank my committee members, Dr. Tammie Spaulding and Dr. Bernard Grela, for their input on this document. I acknowledge the research assistants of the UConn Laboratory for Spoken Language Processing for their role in data collection and organization including Yinyin Gu, Taylor Laubenstein, Alexander Liner, Kayla Marcinczyk, Emily Opramolla, Ann Priolo, Millicent Quevedo, Olivia Stickles, Anna Thomas, and Erin Flanagan. This project was supported by a seed grant award from the Connecticut Institute for the Brain and Cognitive Sciences to R. M. Theodore.

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ABSTRACT

The speech signal is a highly variable signal, which leads to lack of invariance between the acoustic signal and cognitive representations for speech sounds. Previous research has shown that listeners solve the lack of invariance problem, in part, by dynamically modifying the mapping to speech sound categories to reflect systematic variation in the speech input. One example is distributional learning for speech – the degree to which listeners show categorical mapping to speech sound categories changes as function of distributional variability in the input, with performance becoming less categorical as the input becomes more variable. Deficits in the processes that allow listeners to map the acoustic signal to speech sound categories have been implicated as an etiological locus for both language impairment and reading disability, but the existing research literature has not converged on a theoretical understanding of this relationship. Here we examined whether individual variation in language and reading abilities predicts performance in a distributional learning task. Forty adult participants completed a standardized assessment battery to measure cognitive, language, and reading abilities. All participants also completed a distributional learning task in which they completed two blocks of phonetic categorization for words beginning with /g/ and /k/. In one block, the VOTs specifying the /g/ and /k/ words formed narrow distributions (i.e., minimal variability). In the other block, the VOTs specifying the /g/ and /k/ words formed wide distributions (i.e., maximal variability). The slope of the identification function was calculated separately for each block, and the difference between the narrow and wide slopes was used as the measure of distributional learning. The results showed that the category identification slope was shallower in the wide block compared to the narrow block, indicating that distributional learning occurred in the sample as a whole. Performance on the language ability measures was correlated with the magnitude of the distributional learning effect, with increased language ability associated with increased distributional learning. Further analyses revealed that the relationship between language ability and distributional learning was mediated by performance in the narrow block; moreover, reading ability as measured by phonological decoding also influenced performance in the narrow block. Collectively, the results of this study suggest that individual variation in language and reading ability is linked to distributional learning for speech, laying the framework for future investigations that examine the etiological locus of language and reading disorders.

NOTE

This thesis reflects a working draft of a manuscript to be submitted for publication in collaboration with Dr. Rachel M. Theodore. My contributions to this project include stimuli development, experiment programming, data collection, and interpretation of results. I generated the initial draft of the manuscript except for the results session, which was drafted in collaboration with Dr. Theodore.

INTRODUCTION

The goal of the current research is to examine factors that contribute to individual variation in distributional learning for speech perception. This work provides pilot data for subsequent examinations that test the hypothesis that specific language impairment (LI) is linked to deficits in the ability to dynamically modify the mapping to speech sound categories based on variability in the acoustic speech input. We will begin by reviewing the lack of invariance problem for speech perception, and then discuss how adaptability to variation in the speech signal helps to solve the lack of invariance problem. Following, we describe findings from behavioral and computational frameworks that suggest that individual variation in reading and language measures may reflect an individual's degree of adaptability. We conclude the introduction by outlining the current research question and predictions.

Solving the lack of invariance problem for speech perception

Decoding of the acoustic speech signal is accomplished by a listener's perceptual system. The process of decoding is necessary to derive meaning from the signal. In order to do this, listeners track acoustic-phonetic cues in the speech signal and then map this information to speech sound categories. For example, it is well established that voice-onset-time (VOT) is one acoustic-phonetic cue that is used by listeners to recover meaning (Fowler & Magnuson, 2012). Specifically, processing VOT can help a listener distinguish between voiced and voiceless English stops (Lisker & Abramson, 1967). However, a major challenge in the field of speech perception is explaining how listeners achieve perceptual stability given rampant variability in the speech signal, which has been termed the lack of invariance problem for speech perception (Fowler & Magnuson, 2012). Put another way, efficient speech perception requires mapping many distinct acoustic signals to the same speech sound representation. The variability in speech input arises due to many sources, including variation in dialect (Byrd, 1992), speaking rate (Miller & Liberman, 1979), gender (Byrd, 1992), and even individual differences in pronunciation across talkers (Theodore, Miller, & DeSteno, 2009; Newman, Clouse, & Burnham, 2001).

As an illustration, consider factors that influence variability in just one acoustic-phonetic property of speech, VOT for word-initial stop consonants. VOT is an articulatory property of stop consonants that can be measured acoustically as the latency between the stop burst and subsequent onset of periodicity (Lisker & Abramson, 1964; Lisker, & Abramson, 1967). In English, voiced stops are characterized by short VOTs and voiceless stops are characterized by relatively longer VOTs (e.g., Lisker & Abramson, 1964; Lisker, & Abramson, 1967). While this relative timing distinction serves to mark the voicing contrast, the absolute VOT produced for any given stop consonant shows considerable variation from utterance to utterance. For example, speaking rate robustly influences VOT, such that as speaking rate slows, VOTs systematically increase (Miller, Green, & Reeves, 1986). In addition, as place of articulation moves from anterior to posterior in the vocal tract, VOTs systematically increase (e.g., Theodore et al., 2009). One additional source of variability in VOT reflects individual talker differences; even after controlling for place of articulation and speaking rate, some individuals produce longer VOTs than other talkers (Allen, Miller, & DeSteno, 2003; Theodore et al., 2009). Despite such wide variability in the speech signal., listeners nonetheless exhibit stable perceptual processing that supports language comprehension. Previous research suggests that listeners solve the lack of invariance problem by (1) processing variability with respect to discrete perceptual categories, and (2) dynamically modifying these perceptual categories to reflect systematicity in the input (Fowler & Magnuson, 2012). Each solution will be addressed in turn.

Some of the earliest findings in the domain of psycholinguistics provided evidence of categorical perception as a means to solve the lack of invariance problem for speech. In the standard paradigm, listeners are presented with a range of acoustic-phonetic variability along a single dimension (Liberman, Harris, Hoffman, & Griffith, 1957; Eimas, Siqueland, Juscyk & Vigorito, 1971). For example, they may be presented with a VOT continuum ranging from "goal" to "coal", or a vowel formant continuum ranging from "hid" to "head." The members of the continuum are presented to listeners in randomized order, who are then asked to identify each token as a member of one of the two continuum endpoints (Fowler & Magnuson, 2012). The central finding of this work is that listeners' responses to do not show a linear relationship to the acoustic-phonetic property, but rather show a categorical relationship, such that each token is consistently categorized into one of the two endpoint categories. In other words, listeners appear to have a boundary value such that, for example, all VOTs that are shorter than this value are mapped to the voiced category and all VOTs that are longer than this value are mapped to the voiceless category (Lisker & Abramson, 1964; Lisker & Abramson, 1967). Converging evidence for categorical perception comes from discrimination paradigms in where listeners are asked to discriminate between consecutive members of a single acoustic-phonetic continuum. Results from this task show that discrimination is very high for pairs that span the boundary (as revealed by an additional identification task), but is poor for members within the same category, even though the acoustic distance is the same in both cases (Liberman et al., 1957). Strikingly, categorical perception emerges very early in development, with categorical like processing of VOT observed in one-month-old infants (Eimas et al., 1971).

Thus, categorical perception is one mechanism that can help listeners solve the lack of invariance problem. However, it is not sufficient to simply learn a single boundary value for a particular speech sound, given that there are rich contextual influences that govern variability, as described above. For example, to have optimal perception of stop consonants, listeners should be able to adjust the voicing boundary as a function of speaking rate, place of articulation, and who is speaking, given that these factors all systematically influence which VOTs will be present in the speech signal.

Indeed, the second way that listeners solve the lack of invariance problem is by exhibiting functional plasticity in the mapping to speech sounds. In the case of processing VOT perception, Miller, Green, and Reeves (1986) found that the VOT voicing boundary was located at a longer VOT for a slow compared to a fast speaking rate, in line with how these VOTs pattern in speech production (see also Miller & Volaitis, 1989). Likewise, Volaitis and Miller (1992) showed that the voicing boundary for a velar stop continuum was located at a longer VOT compared to the voicing boundary for a labial stop continuum. Other research has shown that even when listeners do not need to modify a category boundary to accommodate systematic variation, they do modify the internal structure of a phonetic category (Theodore, Myers, & Lomibao, 2015). Even though listeners will categorize many acoustic tokens into a single phonetic category, it is not the case that all members are considered equally good members. Rather, some are more prototypical than others, reflecting frequency in the speech input. Research has shown that which members are considered most prototypical can be modified due to many factors, including previous exposure to a talker's voice (Theodore et al., 2015; Drouin, Theodore, & Myers, 2016). Finally, previous research has demonstrated that all categorical perception is not equally categorical. Rather, some speech sounds, such as consonants, tend to be perceived more categorically than other speech sounds, such as vowels (Pisoni, 1975). In addition - and of key relevance to the current work - research has shown that the degree of variability in the speech input fundamentally changes how categorical a person's responses are, even for acoustic-phonetic variability along a single dimension (Clayards, Tanenhaus, Aslin, & Jacobs, 2008).

Clayards and colleagues (2008) examined how variability in the speech input would influence participant's categorical perception of English stop consonants. The authors generated two sets of distributions using items from three VOT continua: *beak* - *peak*, *beach* - *peach*, *bees* - *peas*. Each set contained a distribution of VOTs specifying /b/ and a distribution of VOTs specifying /p/. One set was referred to as the "narrow distributions" and the other set was referred to as the "wide distributions." The two sets of distributions were equal with respect to the number of tokens and the mean VOT value in each distribution. Critically, the sets of distributions varied in terms of their variance. Figure 1 shows a schematized version of the Clayards and colleagues (2008) stimulus set. The narrow set of distributions contained VOT tokens closely distributed around the mean, while the wide set consisted of tokens that were spread relative further from the mean. Manipulating the variance of the sets of distributions allowed the experimenters to assess how variability in the speech signal, specifically in the consistency of VOT production, influenced categorical perception of the stop voicing contrast.

Clayards et al. (2008) exposed twelve monolingual English listeners to the more consistent narrow set of distributions and another twelve to the less consistent wide set. Participants were asked to categorize each stimulus by clicking on the picture that corresponded to the sound that they heard. To assess whether the participants engaged in distributional learning, or in other words, if they modified their categorical perception based on the variability in the input, the researchers derived identification functions from the participant's responses, and compared the slope of the identification function between the two groups. Steeper slopes would indicate that listeners were more certain about whether the acoustic cue they heard indicated a specific speech sound category, either /p/ or /b/, while shallower slopes reflect greater uncertainty. Clayards and colleagues (2008) found that exposure to a particular distribution influenced participants' categorical perception, such that participants exposed to the less consistent set of distributions had shallower slopes, suggesting that they were more uncertain in categorizing sounds from the distribution with greater variability. The differences in slopes of the identification functions indicate that unimpaired, monolingual listeners modify their perception based on variability in the speech signal; they efficiently engage in distributional learning.

Individual differences in statistical and distributional learning have been demonstrated in a number of studies. Listeners show individual variation in their ability to recognize and utilize acoustic-phonetic cues, i.e., vowel formants, present in the speech input to recognize a non-native speech sound contrast (Wanrooij, Escuerdo & Rajimakers, 2013). In a distributional learning study of a non-native speech sound contrast, listeners who used a variety of acoustic cues had improved performance over those who used fewer cues. Furthermore, the ability to learn non-adjacent dependencies in a pseduo-language with high variability is correlated with an individual's ability to process and comprehend relative clauses, suggesting that language processing is mediated by individual variation in statistical learning and speech processing ability (Misyak, Christiansen & Tomblin, 2010; Misyak & Christiansen, 2012). These studies demonstrate that adults with typical language are able to make modifications to their perception of the speech signal, which leads to improved comprehension of the information contained within. Critically, they demonstrate that individuals vary in their ability to adapt to variation.

Research demonstrating that language ability may be mediated by speech perception ability (Misyak et al., 2010; Misyak & Christiansen, 2012) is closely aligned with a vast literature demonstrating that individuals with language impairment show deficits in speech sound perception (Evans, Saffran & Robe-Torres, 2009; Joanisse, Manis, Keating & Seidenberg 2000; Grunow, Spaulding, Gomez & Plante, 2006). Given that individuals with language impairment have deficits specific to recognition, processing, and learning information from the speech stream, we have reason to investigate whether individual differences in language and reading ability are related to inefficient adaptation to variability in the speech signal, which could thus lead to poor mapping of acoustic cues to discrete phonetic categories. We will briefly define language impairment, and then outline evidence demonstrating impairment in areas of understanding and expressing language verbally, deficits in literacy and reading, as well as underlying deficits in speech sound processing.

Specific language impairment (LI)

Specific language impairment (LI) is a neurodevelopmental disorder of unknown etiology that manifests as a delay in the production or understanding of grammatically correct language in the absence of any co-morbid neurological or developmental deficits (Bishop, 2006; Leonard, 1989). The language of children with LI is simplified, inappropriate with immature grammatical structures, as well as a limited expressive vocabulary (Bishop, 2006). They have poor comprehension or receptive language skills (Bishop, 2006), as well as a limited working memory and processing ability for complex grammatical utterances (Bishop, 2006; Marton & Schwartz, 2003). In addition to explicit language deficits, a subset of children with LI have deficits in reading ability (Flax et al., 2003; McArthur, Hogben, Edwards, Heath, & Mengler, 2000). Children with LI and reading difficulties demonstrated poor sight word reading, non-word reading, as well as reading comprehension, rate and accuracy compared to typically developing peers (Flax et al., 2003; McArthur et al., 2000). Accordingly, estimates of co-morbid reading deficits in children with LI range from 55 to 68 percent (Flax et al., 2003; McArthur et al., 2000). The language and reading impairments of children with LI persist into adulthood (Clegg, Hollis, Mawhood, & Rutter, 2005; Tomblin, Freese, & Records, 1992; Poll, Betz, & Miller, 2010; Suddarth, Plante, & Vance, 2012). A longitudinal study following seventeen adults with LI (ALI) into their thirties found that they could be distinguished from their same age peers and siblings on measures of receptive language, expressive vocabulary, phonological processing and short term memory ability (Clegg et al., 2005). Adults with language impairment can also be discriminated from typical language peers based on grammaticality judgements, particularly of verb finiteness, speaking rate, sentence and non-word repetition, written spelling and the amount of spelling errors they produce in written narratives (Tomblin et al., 1992; Poll et al., 2010; Suddarth et al., 2012). Overall, the language and reading difficulties that individuals with LI face as children persist into adulthood, and distinguish them from typical language and reading peers.

Though LI is often diagnosed, discussed, and treated with respect to expressive and receptive language abilities (Paul, 2007; Leonard, 2014), there is a rich literature implicating low level deficits in the earliest mapping from speech acoustics to meaning, leading to deficits in receptive and expressive language ability, as the etiological locus of the disorder. Below we describe evidence from behavioral, computational, and neuroimaging findings attesting that individuals with LI demonstrate deficits in mapping acoustic information from the speech signal to sound categories to derive meaning.

Behavioral evidence. Deficits in speech processing have been well documented for adults and children who have language impairments. These studies suggest that individuals with LI may struggle with adapting to variable information in the speech signal. Children with LI have difficulty identifying consonant sounds in the presence of background noise (Zeigler, Pech-

Georgel, Alario, & Lorenzi, 2005). This difficulty is correlated with deficits in reading and repeating nonwords, or phonological decoding abilities (Ziegler et al., 2005). Children with LI also demonstrate difficulty on categorical perception tasks. Joanisse, Manis, Keating and Seidenberg (2000) directed children with a documented reading impairment and poor language ability to listen to a continuum ranging from /dʌg/ to /tʌg/ and differing only in VOT in incremental steps of 10 ms. They had them point to a picture of /dʌg/ or /tʌg/ after they heard a randomized token from the continuum. They found that children with dyslexia without language difficulties, compared to children with dyslexia and language impairment, had a shallower identification slope between prototypical /d/ and /t/ tokens, suggesting greater uncertainty regarding whether an acoustic token belonged to the /d/ or /t/ category. Their results suggest that participant's language, and not reading, difficulties underlie poor categorical perception. In addition to weak categorical perception abilities, children with LI demonstrate difficulty tracking variable input in the speech signal. Children with LI could not identify word boundaries in a model language by tracking translational probabilities, which indicate that they have difficulty using statistical information to parse the acoustic speech signal to learn or adapt to new rules of language (Evans et al., 2009). A similar pattern has been identified in adults with language difficulties. Adults with LI have demonstrated difficulty learning a cue for word order, non-adjacent dependencies, in an artificial language, while learning of non-adjacent dependencies occurred for adults with typical language ability (Grunow et al., 2006). Overall, these experimental studies suggest that individuals with language and reading deficits demonstrate difficulty detecting, tracking and adapting to variable input in the speech signal.

Computational evidence. Additional evidence demonstrating poor speech perception abilities in individuals with language difficulties has been demonstrated through computational modeling (Joanisse & Seidenberg, 2003). Joanisse and Seidenberg (2003) asked whether an underlying deficit in speech perception leads to a deficit in working memory; which in turn, would impair the acquisition of grammatical structures in individuals with language difficulties. They generated two computational models to simulate processing of syntactic information, one for typical individuals and one for individuals with language impairment. The networks test a hypothetical memory that takes phonological input and returns semantic output that is stored as memory units. Input values in the LI model had an added random digit that made the phonological input, or grammatical structures, more difficult to learn. After running novel sentences through each model, the typical language network was more efficient at recognizing grammatical forms in novel sentences than the impaired network. The conclusions of this modeling experiment suggest that individuals with language difficulties will have trouble deriving meaning from variable information in the acoustic speech stream due to inefficient decoding ability.

Neuroimaging evidence. In addition to strong, converging evidence from behavioral and computational modeling experiments, neurophysiological findings suggest that individuals with language and reading deficits may demonstrate difficulty processing and adapting to distributional information. Previous research has identified areas of the brain that may play a role in recognition and decoding of the speech signal (Benson et al., 2001; Hugdahl et al., 2004). Functional MRI data from twelve language typical adults who passively listened to speech stimuli varying in phonetic complexity were collected and analyzed (Benson et al., 2001). Results indicated that the subject’s bilateral superior temporal sulcus (bSTS) and posterior left superior temporal gyrus (plSTG) demonstrated greater activation as complexity of the stimuli was increased. This suggests that the bSTS and plSTG play a role in decoding and analysis of the speech stream. Adults and children with language impairment who listened passively to real and nonsense speech stimuli demonstrated reduced activation compared to a typical language control group in the bSTS and medial temporal gyri (MTG) (Hugdahl et al., 2004). The findings of these neurophysiological imaging studies suggest that children and adults with language difficulties demonstrate neurophysiological differences in the areas of the brain, specifically the STS and STG, that are responsible for decoding information from the speech stream and mapping to discrete phonetic categories.

The current project

There is a vast amount of literature suggesting that individuals with LI have deficits in speech perception, however there exists no literature that shows how they adapt to variability in the acoustic speech signal. The ability to adapt to variability in the speech signal appears to mediate categorical perception of speech sounds (Wanrooij et al., 2013), as well as the processing and comprehension of language (Misyak et al., 2010; Yurovsky, Case & Frank, in press). This suggests that deficits in the ability to adapt to variability in the speech signal may lead to delay or impairment in language and reading ability. Whether individuals with LI can modify their mapping of speech sounds due to exposure to variable acoustic cues can be demonstrated through distributional learning paradigms, such as the one generated by Clayards and colleagues (2008). The purpose of this study was to test the hypothesis that individual differences in reading and language abilities predicts participants' ability to modify the mapping to speech sound category structure in line with exposure to systematic variability in a distribution of acoustic cues. The current study asks three research questions:

(1) Can distributional learning can be measured through a within-subjects design? An affirmative answer to this question will provide further evidence of rapid adaptation to the

speech input and determine feasibility for follow-up studies that incorporate clinical populations.

(2) Do individual differences in language and reading ability predict participants' ability to modify the mapping to speech sound categories as measured through distributional learning?

(3) Do individuals with LI or RD show deficits in distributional learning for speech?

METHODS

Participants

The participants were forty undergraduate students at the University of Connecticut who were all monolingual speakers of English between 18 and 22 years of age (mean = 19.82, SD = 1.20). Ten of the participants were male, 27 were female, and three preferred not to indicate sex. No participant reported previous difficulty with reading or language, though two participants had a previous history of speech therapy. As described below, five participants met criterion for LI and six participants met criterion for reading disability based on their performance on a standardized battery of assessments. All participants passed a pure tone hearing screening administered at 20 dB for octave frequencies between 500 and 4000 Hz. In accordance with the University of Connecticut Institutional Review Board, participants provided informed consent and received monetary compensation or course credit for participation.

All participants completed a battery of standardized assessments to measure non-verbal intelligence, language, and reading ability. All testing was conducted by the author or undergraduate research assistants who were trained to administer the assessments. Participants' non-verbal intelligence was measured using the Test of Nonverbal Intelligence - Fourth Edition (TONI-4; Brown, Sherbenou, & Johnsen, 2010). This measure was included to ensure that differences in reading and language ability were not attributable to differences in intelligence.

The language component of the assessment battery consisted of a 15-word spelling test, a modified version of the Token Test, and four subtests of the Clinical Evaluation of Language Fundamentals - Fifth Edition (CELF-5; Wiig, Semel, & Secord, 2003). The 15-word spelling test and modified Token Test were administered in order to complete a discriminant analysis to identify LI (Fidler, Plante, & Vance, 2011). The discriminant analysis is a procedure that was specifically designed to identify young adults with unresolved developmental LI and has a reported sensitivity of 80% and specificity of 87%, with a disclosure of previous history of speech-language pathology (SLP) services. If the discriminant analysis indicated that their scores were indicative of language impairment (quantified as positive numbers in the discriminant analysis equation), then we characterized them as LI for the purpose of this pilot study. Three of our forty subjects were identified as LI using this procedure. The four subtests of the CELF included measures of receptive (Understanding Spoken Paragraphs, Semantic Relationships) and expressive (Recalling Sentences, Formulated Sentences) language.

The reading component of the assessment battery included timed and untimed measures of reading fluency and phonological decoding, and an untimed measure of reading comprehension. The timed measures consisted of the Sightword Efficiency (reading fluency) and Phonological Decoding (phonological decoding) subtests of the Test of Word Reading Efficiency-second edition (TOWRE; Torgesen, Wagner, & Rashotte, 1999). The untimed measures consisted of the Word Identification (reading fluency) and Word Attack (phonological decoding) subtests of the Woodcock Reading Mastery Test- third edition (WRMT; Woodcock, 2011). The Passage Comprehension subtest of the WRMT was used to measure reading comprehension. Participants were characterized as reading disabled (RD) if they scored at or below the 25th percentile on two or more reading subtests (Perrachione, Del Tufo, & Gabrielli, 2011; Joanisse et al., 2000)

As described in detail below, six participants were excluded from the final analyses due to a failure to meet criterion for inclusion in the distributional learning measure. Table 1 shows mean, standard deviation, and range of performance for each measure of the assessment battery for the 34 participants that were included in the distributional learning analysis. Performance is shown in terms of percentile except for the discriminant analysis, 15-word spelling test, and modified token test, which are shown in terms of raw score. Inspection of this table reveals that a wide range of language and reading abilities were present, indicating that our sample is suitable for use in examining individual differences in distributional learning.

Stimuli

The stimuli consisted of auditory tokens of *goal, coal*, *gain*, and *cane* produced by a female speaker that varied in word-initial VOT. The stimuli were drawn from those used in Theodore and Miller (2010), to which the reader is referred for comprehensive details on stimulus creation. In brief, the stimuli were drawn from two VOT continua, one that ranged from *goal* to *coal* and one that ranged from *gain* to *cane*. Each continuum was created using a naturally produced token as the voiced-initial endpoint (i.e., goal, gain). The LPC-based speech synthesizer in the ASL software package (Kay Elemetrics) was used to successively increase word-initial VOT in 4-5 ms increments, each time generating a new speech token. For each continuum, this procedure resulted in word-initial VOTs that perceptually ranged from /g/ to /k/. Twelve tokens from each continuum were selected for further use, with VOTs ranging from 11 ms to 119 ms VOT in approximately 10 ms increments.

Following the methods outlined in Clayards and colleagues (2008), the selected tokens were arranged into three sets, one for use in the narrow block, one for use in the wide block, and one for use during practice. The sets for the narrow and wide blocks each consisted of 236 tokens, and contained equal numbers of each of the four words. Moreover, both sets contained one distribution of VOTs specifying /g/ and another distribution of VOTs specifying /k/, with the mean of the /g/ and /k/ distributions identical between the narrow and wide sets. The key distribution between the narrow and wide sets is the variance of the /g/ and /k/ distributions, with the variance smaller in the narrow compared to the wide set. Thus, this procedure yields two blocks of stimuli that only differ with respect to variability of the VOT distributions. Figure 2 shows histograms of the VOTs in each of the narrow and wide stimulus sets. Table 1 shows the mean and SD of each distribution.

The practice set contained twelve tokens that consisted of three repetitions of the *gain*, *cane, goal,* and *coal* token that represented the mean VOT of the appropriate /g/ or /k/ distribution.

Procedure

All testing was completed in a sound attenuated booth. Participants were seated at a table that contained a computer monitor and a response box. Auditory stimuli were presented via headphones at a comfortable listening level that was held constant across participants. Each participant completed two blocks of a phonetic categorization task, one using the narrow stimulus set and one using the wide stimulus set. Order of the blocks varied across participants, with 24 completing the narrow block first and 16 completing the wide block first. On each trial, participants were instructed to listen to each item and indicate whether the item sounded most like *gain, cane, goal,* or *coal*. They indicated their choice by pressing a button on the response box that was labeled with each word. Participants were instructed to make their decision as quickly as possible without sacrificing accuracy and to guess if they were unsure on a particular trial. Prior to the first block, participants completed 12 practice trials using the practice stimulus set. The instructions were repeated prior to the onset of the first experimental block. The time to complete the distributional learning task was approximately 30 minutes.

RESULTS

For each participant, mean percent /k/ responses was calculated for each VOT separately for each of the narrow and wide blocks. Following standard convention (e.g, Theodore et al., 2015; Volaitis & Miller, 1992), probit analyses were used to determine an identification function for each of the blocks by fitting an ogive function to mean percent /k/ responses on a participant-by-participant basis. The mean of the ogive function thus serves as a metric of the /g/ - /k/ boundary in that it measures the VOT corresponding to 50% /k/ responses. The standard deviation of the ogive function serves as a metric of the identification slope, with increased values indicating a shallower (i.e., less categorical) identification function. Figure 3 shows an illustration of this method for one participant. This method provided three dependent measures for each participant including the slope of the function for the narrow block, the slope of the function for the wide block, and a measure reflecting distributional learning calculated as the difference between the slopes of the narrow and wide blocks.

Given that the dependent measures are parameters derived from the fitted ogive functions, any participant for whom the fitted function was a poor fit to the percent /k/ responses was excluded from future analyses. A poor fit was defined as $r < .80$ for the relationship between the fitted function and the original responses. Two participants were excluded for this reason. Consistent with the exclusion criteria used in Clayards and collegues (2008), four additional participants were excluded because their category boundary (quantified as the mean of the fitted ogive) deviated more than 15 ms beyond the intended category boundary. This is necessary because any deviance from the intended category boundary interferes with the distributional manipulation in the stimulus set. We present the results below for the 34 participants that were included in the analysis according to the three research questions examined in this study.

Can distributional learning can be measured through a within-subjects design?

Figure 4 shows the mean identification slope across the 34 participants for the narrow and wide blocks. Visual inspection suggests that distributional learning is indeed present; the slope of the wide block is located at a longer value compared to the slope of the narrow block. Indeed, a paired t-test confirmed that the slopes of the wide block were significantly higher than the slopes of the narrow block [$t(33) = 3.909$, $p < 0.001$], indicating less categorical responses for the more variable block.

Recall that the order in which participants completed the narrow and wide blocks varied among the participants. In order to examine possible effects of order on the identification slopes, we submitted the slopes to a mixed ANOVA with the within-subjects measure of blocks (narrow vs. wide) and the between-subjects measure of order (narrow-wide vs. wide-narrow). The results of the ANOVA showed a main effect of block [F(1,32, = 15.357, $p < 0.001$], as expected based on the t-test. Critically, there was no main effect of order [F(1,32, = 0.002, $p = 0.958$], nor an interaction between block and order [F(1,32, = 1.160, $p = 0.289$], indicating that order in which participants completed the narrow and wide blocks did not influence their identification slopes.

Is distributional learning linked to individual differences in language and reading ability?

In order to examine the relationship between performance on the standardized assessment battery and the distributional learning task, we calculated correlations (Pearson's r) between each measure of the assessment battery and each of our three dependent measures. The full correlation matrix is shown in Table 3.

Consider first the relationship between language and reading abilities and our measure of distributional learning (i.e., the difference between the wide and narrow slopes). There was a significant correlation between discriminant analysis score and distributional learning (r =-0.348, $p = 0.044$), and between the Semantic Relations subtest and distributional learning ($r = 0.355$, $p = 0.039$). For both of these measures, the direction of the correlation is that as performance on the language measure increased, so too did the magnitude of the distributional learning effect. Recall that the discriminant analysis score is calculated using performance on the 15-word spelling test and the modified token test. The relationship between the discriminant analysis score and distributional learning reflects the influence of performance on the 15-word spelling test ($r = 0.389$, $p = 0.023$), with no observed relationship between performance on the modified token test and distributional learning ($r = 0.092$, $p = 0.600$).

Next, consider the relationship between the standardized assessment measures and slope of the identification function for the wide distributions. Strikingly, none of the assessment measures show a reliable relationship with identification slope in the wide block. This pattern suggests that the influence of language ability on distributional learning is linked to performance in the narrow block. Indeed, the final consideration of the correlation matrix shown in Table 3 is the relationship between the assessment measures and slope of the identification function for the narrow distributions. There was a significant correlation between the slope of the narrow block and scores for the discriminant analysis ($r = 0.593$, $p < 0.001$), 15-word spelling test ($r = -0.586$, $p < 0.001$), and Semantic Relationships subtest ($r = -0.524$, $p = 0.001$), as was observed for the distributional learning measure. In addition, there was a significant relationship between the slope of the narrow block and the two reading measures associated with phonological decoding, including the Phonological Decoding subtest of the TOWRE ($r = -0.355$, $p = 0.039$) and the Word Attack subtest of the WRMT ($r = -0.356$, $p = 0.039$). For all of these measures, the direction of the relationship was the same – as reading ability and language ability increased, the slope of the identification function in the narrow block decreased, indicating an identification function that was more categorical. The differential relationship between language ability and the identification slope for the narrow versus wide distributions is illustrated in Figure 7 for performance on the discriminant analysis measure.

Collectively, the results of these analyses indicate that individual variation in language and reading ability is linked to distributional learning for speech by influencing the degree to which listeners capitalize on systematic variation in the speech input. Specifically, those with poorer language and phonological decoding abilities failed to show a steep identification function for the narrow distributions such that the difference between the wide and narrow functions was minimal. In other words, these individuals processed the minimally variable input in the narrow block as if it were more equivalent to the maximally variable input in the wide block.

Do individuals with LI or RD show deficits in distributional learning for speech?

As described in the Participants section, six participants were categorized as LI and six participants were categorized as RD based on their performance on the standardized assessment battery. Three of the six LI participants were part of the six participants excluded due to performance on the distributional learning task, leaving three remaining participants who meet criterion for LI. Given the small number of participants who met the LI and RD criteria, we present the following analyses as preliminary in nature.

In order to examine whether individuals with LI show a deficit in distributional learning, we examined performance separately for those without LI (n = 33) and those with LI (n = 3) in terms of their slopes for the narrow and wide blocks. As shown in Figure 5, individuals with LI show no difference in the slope for the narrow and wide blocks. This is in stark contrasts to the difference between the narrow and wide blocks observed for the individuals without LI, and provides preliminary evidence that distributional learning is impaired in the LI population.

In order to examine whether individuals with RD show a deficit in distributional learning, we performed a parallel analysis between individuals without RD (n = 30) and individuals with RD (n = 6). As shown in Figure 6, individuals with RD showed a higher (i.e., more shallow) identification slope in the narrow condition compared to individuals without RD – but, critically, there was a difference between the wide and narrow blocks for the RD participants. This finding suggests that while identification may be less categorical overall in the RD population, distributional learning is intact in this population.

DISCUSSION

In order to map the speech signal to representations that support language comprehension, listeners must accommodate rich variability in the acoustic speech stream. One mechanism that supports this process is distributional learning for speech. The degree to which a listener shows categorical processing of acoustic variability is fundamentally linked to the degree of variability, with increased categorical processing observed for consistent compared to inconsistent input (Clayards et al., 2008; Kleinschmidt & Jaeger, 2015). The literature to date on distributional learning for speech has not considered how the ability to dynamically modify the mapping to speech sound categories given exposure to acoustic variability may be affected by individual differences in language ability, which was the focus of the current research.

Though individuals with LI demonstrate impairments in statistical learning and categorical perception, we know little about whether they are able to modify their representation of phonetic category structure in response to variability in the speech signal. Poor adaptability could lead to impairments in efficient processing and comprehension of speech sounds and language (Wanrooij et al., 2013; Misyak et al., 2010; Yurovsky et al., in press). We predicted that young adults who have poor language abilities would demonstrate a reduced ability to modify their mapping in response to variable acoustic information, manifesting in no difference in the slopes of their identification functions for more versus less consistent input distributions.

Our experimental aims for the current work were to examine (1) whether distributional learning could be measured through a within-subjects design, (2) whether an individual's differences in reading and language ability predict their distributional learning ability, and (3) whether participants diagnosed with LI and RD present with impairment in distributional learning. We address our findings with respect to each experimental aim in turn below, and then broadly discuss strategies for future work.

In our first aim, we asked whether distributional learning could be measured using a within-subjects design, given that previous examinations used between-subjects designs exclusively (Clayards et al., 2008; Kleinschmidt & Jaeger, 2015). We modified the Clayards et al. (2008) paradigm such that each participant heard both sets of input distributions (i.e., narrow and wide variances). Robust distributional learning was observed in our sample as a whole, with steep identification slopes observed for the narrow compared to the wide distributions. That we were able to replicate Clayards et al. (2008) with a within-subjects design provides clear evidence that suggests that distributional learning is a rapid, dynamic method of adaptation such that it occurs on a time-course consistent within a single experimental session. Ongoing work in our laboratory aims to model the time-course of adaptation using the Bayesian belief-updating framing outlined in Kleinschmidt & Jaeger (2015). Our success in replicating Clayards and colleagues (2008) findings with a within-subjects design speaks to feasibility in using this paradigm in future experiments that incorporate clinical populations.

For our second experimental aim, we asked whether individual differences in participant's language and reading abilities predict the magnitude of distributional learning. The current work provides preliminary evidence that indeed, individual variation in language ability and (to some degree) reading ability mediates distributional learning. Though we found great variability in terms of scores on our language and reading measures, we found converging relationships between poor scores on our language measures and inefficient distributional learning. This finding supports computational frameworks that suggest that deficits in speech perception ability may lead to difficulty processing and comprehending language (Joanisse & Seidenberg, 2003). As distributional learning in the current work is measured by the difference between participant's identification slopes of the wide and narrow sets of distributions, it is critical to examine whether individual differences in reading and language ability predict poor adaptation in both sets, or rather have differential influences on the narrow and wide sets. We find no relationships between the language/reading measures and participants' categorization of the wide input distributions. Critically, we found that poor performance on language and decoding measures showed a strong relationship to performance for the narrow input distributions, with poorer language and decoding ability associated with less categorical identification slopes. To review, the tokens in the narrow sets of distributions are arranged such that the consistency in the speech input is optimized. Thus, it seems that individuals with poor language and reading abilities fail to take advantage of systematicity in the speech signal, consistent with previous findings demonstrating that individuals with deficits in language processing abilities show poor adaptability to structured variation when engaging in statistical learning of nonadjacent dependencies (Misyak et al., 2010). This finding illustrates that speech perception and processing difficulties in individuals with language and reading difficulties may lead to greater uncertainty regarding any input in the speech signal, regardless of consistency.

In our third aim we asked whether individuals identified by our study as language impaired or reading impaired would fail to show evidence of distributional learning. Our results provide clear, preliminary evidence that indicating that distributional learning may be absent in individuals with LI. Unlike our participants with typical language, there was no difference in the slope of the identification function between the narrow and wide input distributions. In contrast, individuals with RD showed evidence of distributional learning, though its magnitude was numerically decreased compared to the individuals without RD. Collectively, these results provide preliminary evidence indicating that distributional learning may be an impairment that is specific to LI, a finding that may help bring resolution to the literature implicating deficits in low-level speech perception abilities as an etiological locus of both LI and RD. However, only one of our three LI subjects was not identified as co-morbidly reading impaired; therefore, we require further evidence to rule out the interactions between reading and language ability as a function of poor distributional learning in individuals with LI.

Future work

The etiology of LI is contested in the current literature. Our results add to the body of evidence indicating that the underlying etiology of LI is may be due to deficits in speech perception. We will briefly discuss other etiological proposals and then discuss our contribution. Many theories have been proposed to explain the etiology of language (and reading) deficits in individuals with language impairment (Leonard, Sabbadini, Leonard, Volterra, 1987; Tallal, Stark & Mellits, 1985; Hsu & Bishop, 2011; Ullman & Pierpont, 2005). One theory follows that the etiology of LI can be attributed to deficits in learning or applying the linguistic rules of English, with some positing that LI results in an underlying deficit in applying morphophonemic rules, leading to errors in the production of grammatical surface forms (Leonard et al., 1987). Others suggest that deficits in a single underlying grammar, resulting from genetic abnormalities, manifests in the language deficits experienced by individuals with LI (Gopnik & Crago, 1991; Leonard, McGregor, & Allen, 1992). Others propose that the etiology of LI in children occur from deficits in auditory temporal processing, such as characterizing patterns of sequences of light flashes and tones as well as discrimination of syllables varying in VOT (Tallal et al., 1985). However, these theories fail to account for research demonstrating neurobiological differences and differences in speech processing and perception abilities between individuals with and without (Bishop, Carlyon, Deeks, & Bishop, 1999).

Two etiological accounts of LI that do account for speech perception ability are the statistical learning deficit hypothesis (Hsu & Bishop, 2011) and the procedural deficit hypothesis (Ullman & Pierpont, 2005). Hsu and Bishop (2011) propose that LI manifests as a deficit in statistical learning of grammatical forms and not a deficit in learning grammatical rules. Similarly, Ullman and Pierpont (2005) implicate deficits in the procedural memory system as the etiology LI. The procedural memory system establishes and facilitates activation of new sensorimotor plans, such as coordination and motoric functioning, manipulation of visual-spatial imagery, and performance on tasks of working memory. Ullman and Pierpont (2005) suggest that deficits in the procedural memory system can explain the linguistic and – critically – the nonlinguistic deficits in individuals with LI. Our results support both the procedural deficit hypothesis and the statistical learning deficit hypothesis, as distributional learning is a task that may be mediated by procedural memory and statistical learning abilities.

Summary

Our findings provide preliminary evidence for identifying areas of the brain that may mediate distributional learning ability. Furthermore, our data supports studying the neural mechanisms of phonetic category structure, representation and plasticity, through neurophysiological measures such as fMRI. The posterior superior temporal gyrus (pSTG) is responsible for processing category goodness of tokens to phonetic categories and the superior temporal sulcus (STS) has a role in decoding and analysis of the speech signal (Myers, 2007; Myers & Theodore, 2017; Benson et al., 2001; Hugdahl, et al., 2004). If we find that individuals with LI demonstrate attenuated activation in the pSTG or STS during speech categorization tasks, then this would provide further neurological evidence that poor distributional learning and speech perception is a possible etiology of language and reading difficulties in this population.

Furthermore, replication of our experiment in the scanner could reveal new neurological areas in typical individuals that are responsible for distributional learning and how they may be impaired in individuals with LI. Collectively; these future studies would provide powerful evidence for clinicians to improve differential diagnosis and clinical researchers to develop viable treatment methods for these individuals. Ongoing research is aimed at examining these possibilities.

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Table 1

Mean and standard deviation (in parentheses) of the VOT distributions specifying /g/ and /k/ for the narrow and wide distributions.

Distribution	**/g/**	**/k/**
Narrow	41 (8)	91 (8)
Wide	41 (12)	91 (12)

Table 2

Mean, standard deviation, and range for each measure of the standardized assessment battery. Numbers in bold indicate percentiles; numbers that are not in bold indicate raw scores.

Test	Construct	Mean	SD	Range
TONI	Nonverbal intelligence	**47**	**19**	**14 – 90**
Discriminant Analysis	Language impairment	-1.1	0.8	-2.4 – 1.2
15-Word Spelling Test	Spelling	12	2	2 – 14
Modified Token Test	Receptive language	37	4	28 – 44
CELF – Formulated Sentences	Expressive language	**57**	**27**	**5 – 95**
CELF – Recalling Sentences	Expressive language	**66**	**20**	**25 – 98**
CELF – Understanding Spoken Paragraphs	Receptive language	**38**	**24**	**2 – 84**
CELF – Semantic Relationships	Receptive language	**68**	**23**	**16 – 95**
TOWRE – Sightword Efficiency	Reading fluency	**69**	**25**	**12 – 98**
TOWRE – Phonological Decoding	Decoding fluency	**72**	**19**	**21 – 98**
WRMT – Word Identification	Reading fluency	**55**	**19**	**6 – 88**
WRMT – Word Attack	Decoding fluency	**46**	**28**	**2 – 92**
WRMT – Passage Comprehension	Reading comprehension	**41**	**22**	**3 – 73**

Table 3

Pearson's correlation (*r*) between the measures of the standardized assessment battery and identification slope for the narrow distributions (N), identification slope for the wide distributions (W), and the distributional learning measure (W-N).

Test	Construct	Slope (N)	Slope (W)	Slope (W-N)
TONI	Nonverbal intelligence	-0.299	-0.173	0.112
Discriminant Analysis	Language impairment	**0.593*** **	0.164	**-0.348***
15-Word Spelling Test	Spelling	**-0.586*** **	-0.096	**0.389***
Modified Token Test	Receptive language	-0.256	-0.154	0.092
CELF – Formulated Sentences	Expressive language	-0.266	-0.021	0.193
CELF – Recalling Sentences	Expressive language	-0.154	-0.029	0.100
CELF – Understanding Spoken Paragraphs	Receptive language	-0.312	-0.113	0.164
CELF – Semantic Relationships	Receptive language	**-0.524****	-0.077	**0.355***
TOWRE – Sightword Efficiency	Reading fluency	-0.243	-0.059	0.230
TOWRE – Phonological Decoding	Decoding fluency	**-0.355***	-0.017	0.288
WRMT – Word Identification	Reading fluency	-0.220	-0.235	0.007
WRMT – Word Attack	Decoding fluency	**-0.356***	-0.043	0.307
WRMT – Passage Comprehension	Reading comprehension	-0.130	-0.200	0.038

*$p < .05$, **$p < .01$, ***$p < .001$

Figure 1

Representative input for the narrow and wide VOT distributions presented in Clayards et al. (2008).

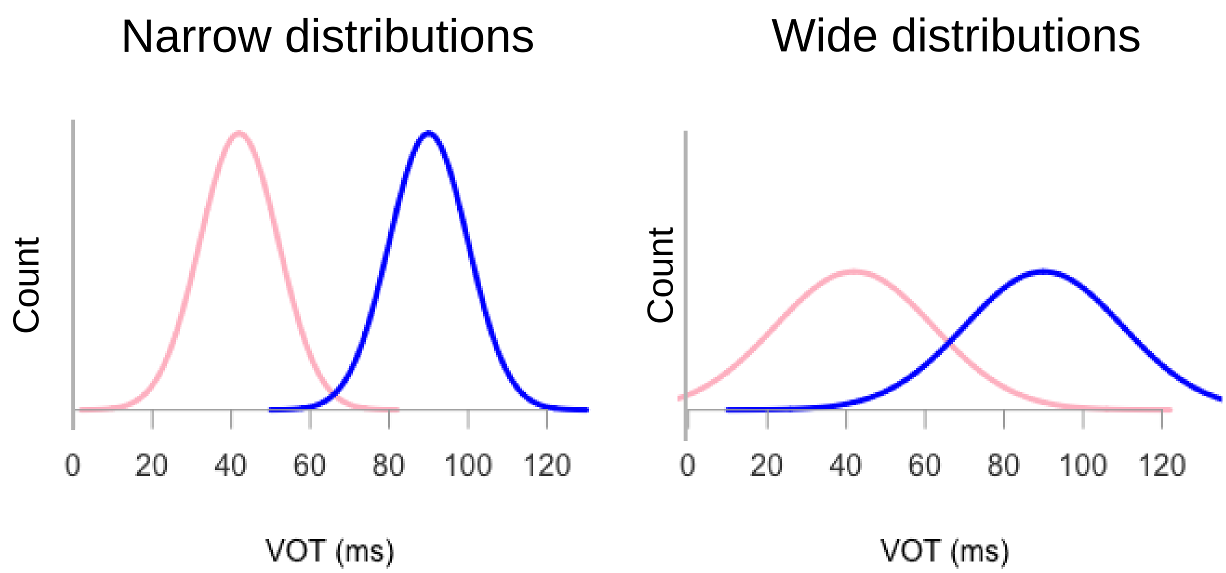


Figure 2

Histograms of the VOTs specifying /g/ and /k/ for the narrow and wide distributions for the stimuli used in the current experiment.

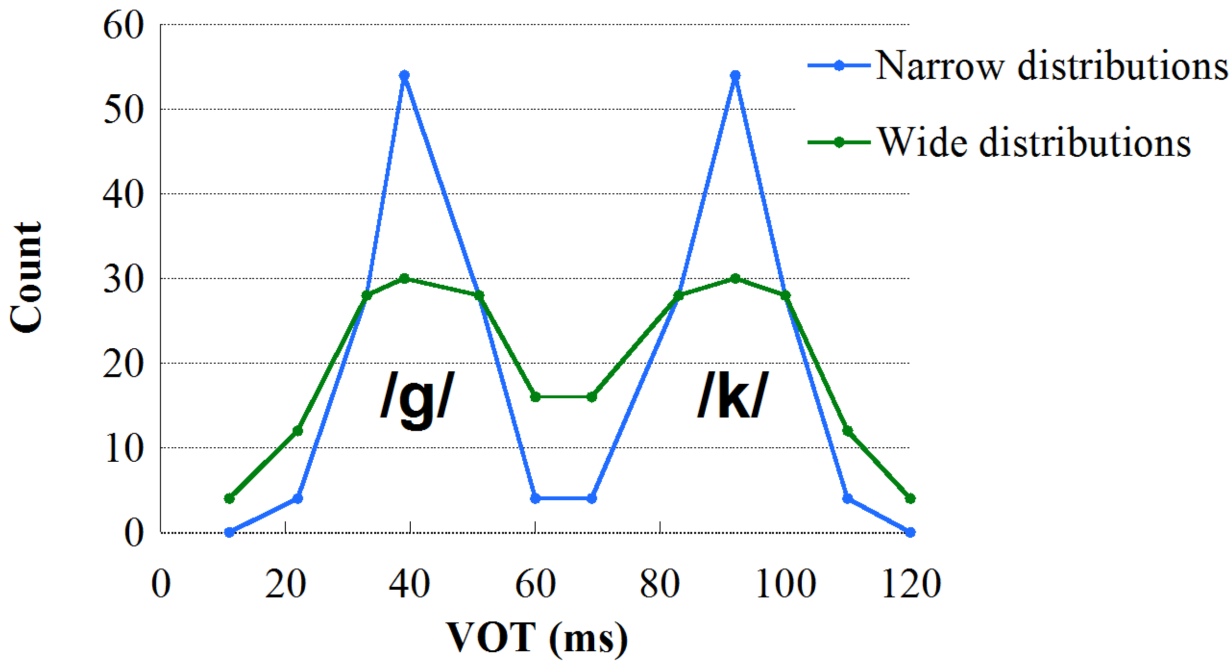
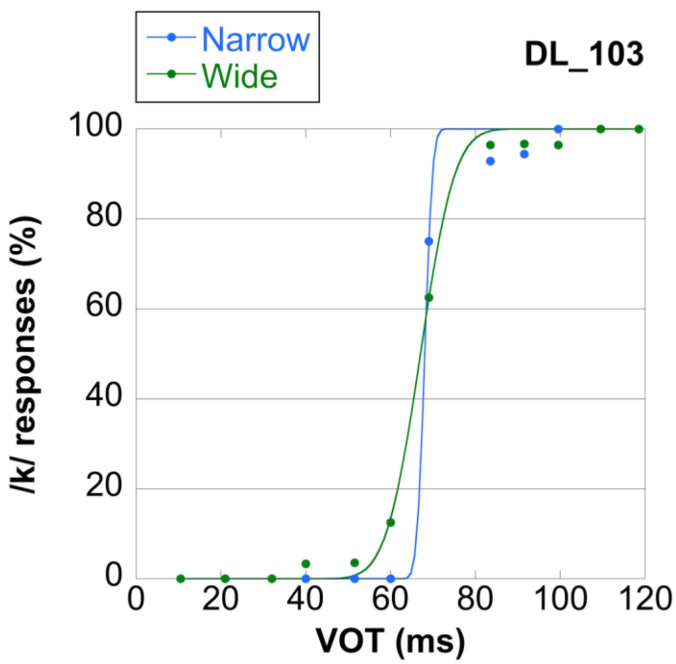


Figure 3

Representative example illustrating the curve-fitting method used to derive the identification slope. Each dot represents mean percent /k/ responses for the associated VOT. The solid lines show the fitted ogive function for each distribution. The mean (μ) and standard deviation (σ) of the ogive function were used to measure the category boundary and identification slope, respectively. The difference between the wide and narrow slopes was used as a measure of distributional learning.



Distribution	**μ**	**σ**	***r***
Narrow (N)	68	1.43	0.99
Wide (W)	67	6.35	0.99
W - N	=	*4.92*	

Figure 4

Mean identification slope for the narrow and wide distributions.

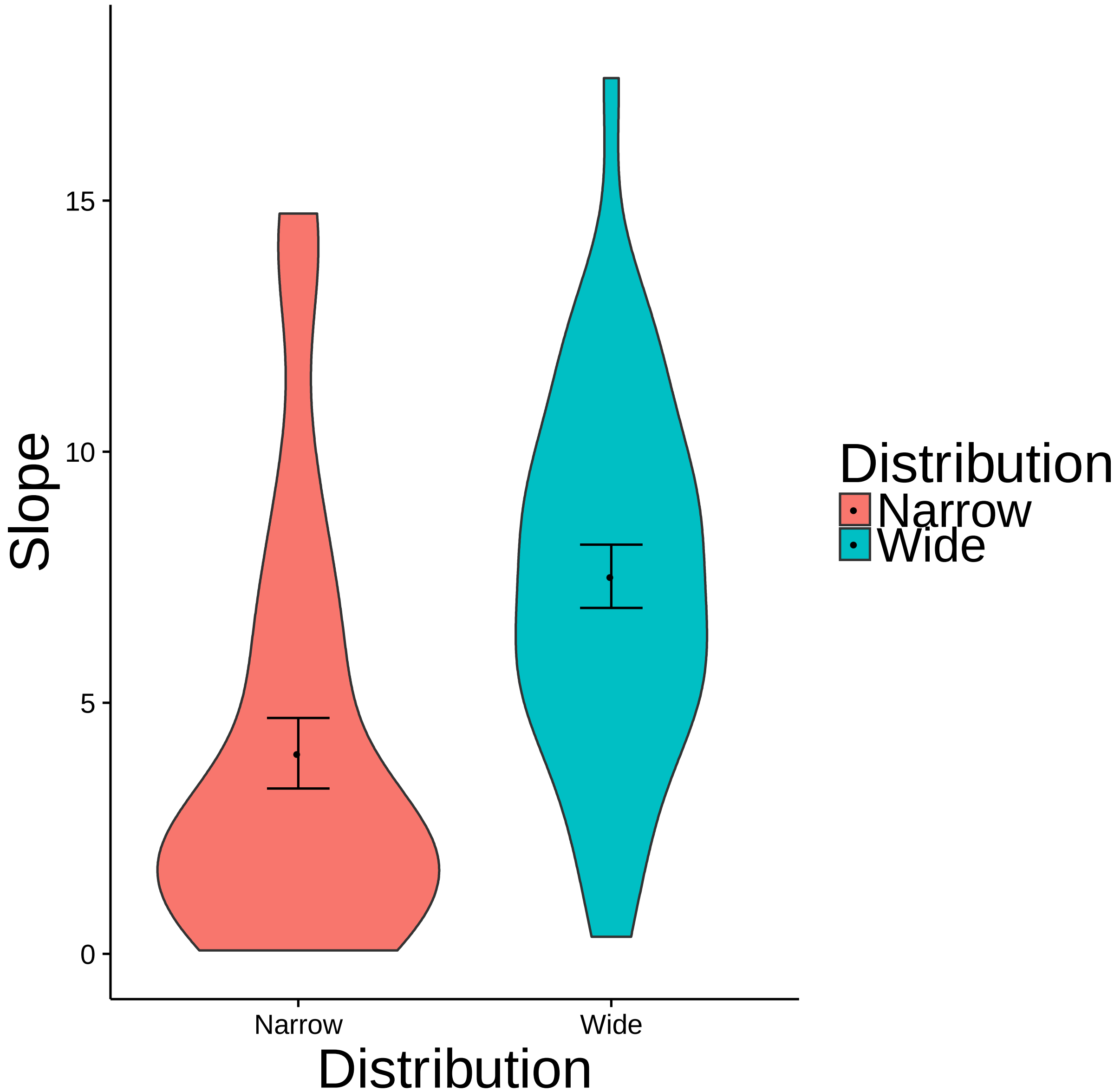


Figure 5

Mean identification slope for the narrow and wide distributions for the control (n = 33) and LI (n = 3) participants.

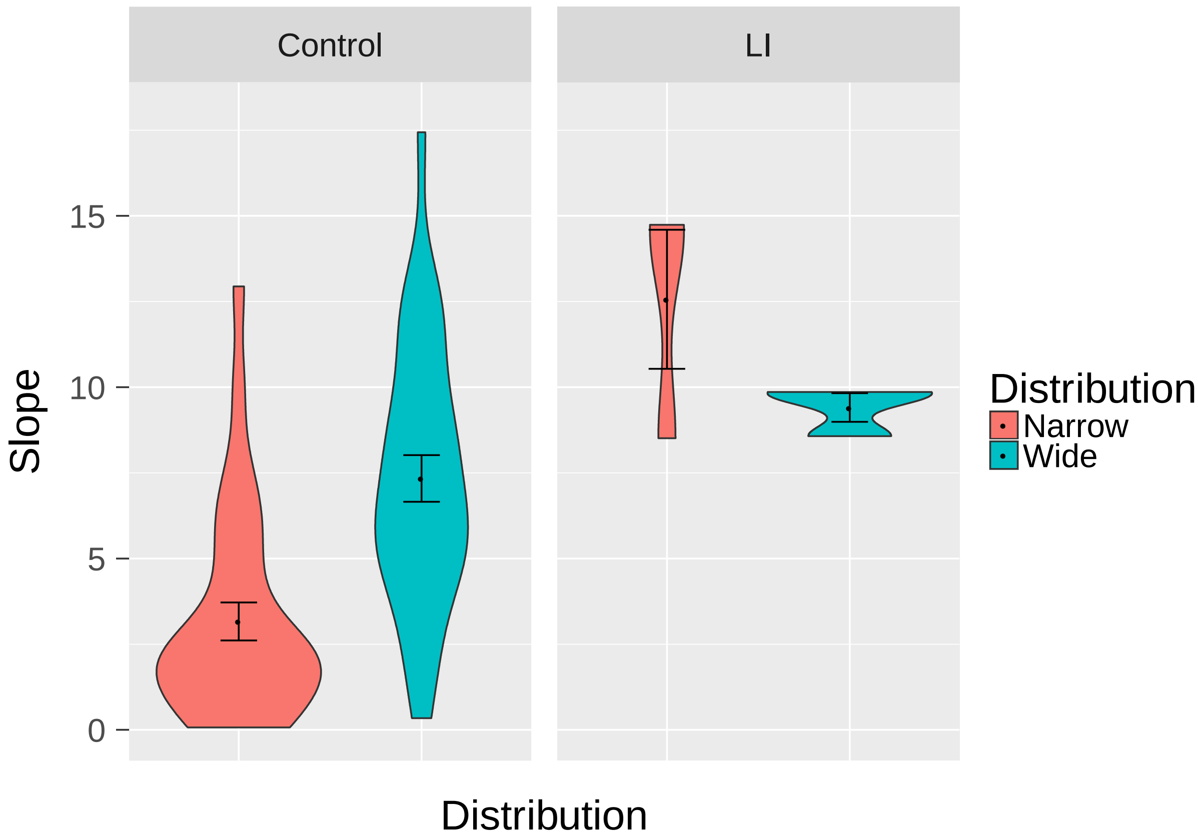


Figure 6

Mean identification slope for the narrow and wide distributions for the control (n = 30) and RD (n = 6) participants.

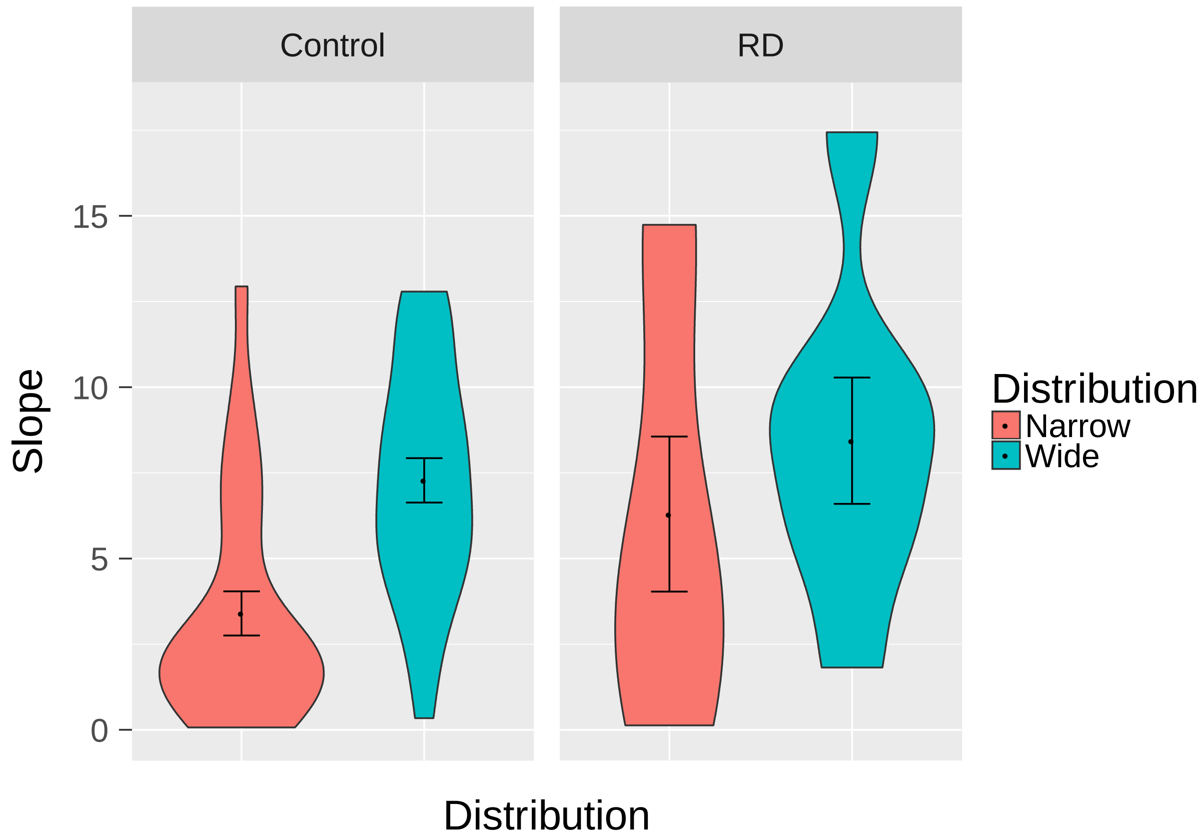


Figure 7

Relationship between discriminant analysis Score and identification slope for the narrow (left panel) and wide (right panel) distributions. Note that higher numbers on the discriminant analysis measure indicate poorer language ability.