6-1-2015

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Published In

Journal of speech, language, and hearing research : JSLHR, 58, 3, 934-945.

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Gabay, Y, Thiessen, D.E., & Holt, L.L. (in press). Impaired statistical learning is developmental dyslexia. To appear in *Journal of Speech Language and Hearing Research*. http://jslhr.pubs.asha.org/

Abstract

Purpose: Developmental dyslexia (DD) is commonly thought to arise from phonological impairments. However, an emerging perspective is that a more general procedural learning deficit, not specific to phonological processing, may underlie DD. The current study examined whether individuals with DD are capable of extracting statistical regularities across sequences of passively-experienced speech and non-speech sounds. Such statistical learning is believed to be domain-general, to draw upon procedural learning systems, and to relate to language outcomes. *Method*: DD and control groups were familiarized with a continuous stream of syllables or sine-wave tones, the ordering of which was defined by high or low transitional probabilities across adjacent stimulus pairs. Participants subsequently judged two three-stimulus test items with either high or low statistical coherence as the most similar to the sounds heard during familiarization. *Results:* Like control participants, the DD group was sensitive to the transitional probability structure of the familiarization materials, as evidenced by above-chance performance. However, DD participants' performance was significantly poorer than controls across linguistic and non-linguistic stimuli. Additionally, reading-related measures were significantly correlated with statistical learning performance of both speech and non-speech material. *Conclusions:* Results are discussed in light of procedural learning impairments among participants with DD.

Keywords: Developmental dyslexia, implicit learning, procedural learning, statistical learning, statistical computations, word segmentation.

1. Introduction

Fundamental language skills such as reading are learned early in life and are culturally dependent. One psychological process that has been suggested to be involved in learning to read is the ability to detect statistical regularities. Reading involves the mapping between phonology, the sounds of the language, and orthography, their arbitrary visual forms. The correspondence between phonology and orthography is complex in languages like English. For example, the vowel "e" is pronounced as /ɛ/ in a word like BED, but as /i/ when paired in an "a," as in BEAD. Although many of these correspondences are taught explicitly in learning to read, learning models emphasize that emergent statistical regularities among phonology-orthography correspondences are also important (McClelland & Patterson, 2002; Seidenberg & McClelland, 1989). Specifically, because the number of phonology-orthography correspondences is vast (more than 1,000 rules according to the dual route cascade model of reading; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), effective learners may rely upon emergent statistical regularities to support explicit instruction.

Consistent with this claim, Arciuli and Simpson (2012) observed that reading abilities among both adults and children are highly correlated with the ability to extract visual statistical structure from the environment. Similarly, a recent study demonstrated that reading proficiency among native American-English adult second-language learners of Hebrew is positively correlated with the ability to extract structure from the environment (Frost, Siegelman, Narkiss, & Afek, 2013). Specifically, the ability to track regularities in a continuous stream of visual shapes correlates with performance on tasks that monitor the assimilation of the structure of Hebrew words via morphological priming. Similarly, sensitivity to statistical regularities is also found to contribute to language proficiency. Evans, Saffran, and Robe-Torres (2009) have demonstrated that the ability to track regularities is positively correlated with vocabulary growth among children. Taken together, these independent observations suggest that sensitivity to statistical regularities may impact reading development by enabling detection of probabilistic correspondences among letters and phonemes and the detection of regularities that exist among letters (transitional probabilities between letters). Moreover, it may enhance vocabulary growth which, in turn, can contribute to reading performance (Biemiller, 2003).

1.1 Developmental Dyslexia

Developmental Dyslexia (DD) is one of the most frequent neurodevelopmental disorders. It is characterized by selective impairment in reading skill acquisition despite conventional instruction, adequate intelligence, and sociocultural opportunity. DD is fairly widespread, but its exact prevalence is uncertain (estimate range from 5-17%; Shaywitz & Shaywitz, 2005). It is more frequently reported in males (Démonet, Taylor, & Chaix, 2004) and its frequency differs across languages (Lindgren, De Renzi, & Richman, 1985). The typical presenting symptoms of DD are difficulties in reading, writing and spelling as well as deficits in word identification and phonological decoding (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Although progress has been made in the past decades, the underlying cognitive and biological mechanisms of DD are still under extensive debate (for a review see, Démonet, Taylor, & Chaix, 2004).

1.2 Phonological Deficit Account

The classic approach views DD as stemming from a phonological deficit (Snowling, 2000). By this account, dyslexia is presumed to arise from a deficit in direct access to, and manipulation of, phonemic language units retrieved from long-term declarative memory (Snowling, 2000). Indeed, phonological impairments are among the central symptoms associated with DD (Ramus et al., 2003). Phonological awareness (sensitivity to the sound structure in a word), verbal short term memory and lexical retrieval are impaired in DD (Vellutino et al., 2004). However, an accumulating body of evidence demonstrates that people with DD have a wide range of non-linguistic deficits. These include impairments in motor functions (Fawcett & Nicolson, 1995; Nicolson & Fawcett, 1994), attention deficits (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Helland & Asbjørnsen, 2000), as well as procedural learning impairments (Lum, Ullman, & Conti-Ramsden, 2013). One difficulty for the phonological hypothesis is its inability to account for these additional impairments (Brookes, Nicolson, & Fawcett, 2007; Démonet et al., 2004). Furthermore, phonological impairments are observed also in individuals who do not have DD (Morris et al., 1998). It is possible that phonological deficits may be symptoms arising from another underlying cause.

1.3 Procedural Learning Deficit Account

An emerging perspective in dyslexia research is that difficulty in phonology, reading, writing and spelling skills among people with DD may be related to a more general learning deficit, not specific to phonological processing or to speech materials (Nicolson & Fawcett, 2011). According to this perspective, DD may be related to selective disruption of the procedural learning system that sub-serves the learning and control of established sensorimotor and cognitive habits, skills, and procedures (Alvarez & Squire, 1994). This deficit is posited to stem from dysfunction within one or more of the brain areas related to this system (e.g., the prefrontal cortex around Broca's area, the parietal cortex and sub-cortical structures including the basal ganglia and the cerebellum). By this perspective, a procedural learning impairment disrupts *automatization of skill and knowledge,* which may potentially impact grapheme-phoneme conversion, word recognition, verbal working memory, and learning orthographic regularities -- thereby contributing to reading impairment. In addition, this approach suggests that procedural learning system impairment in DD may lead to *mild motor and articulatory problems* that result in impoverished representations of the phonological characteristics of speech and concomitant difficulties in grapheme-phenome conversion and in learning to read. Since the procedural learning system involves a network of multiple brain regions, this perspective postulates that it is possible to observe a range of manifestations of DD (Nicolson & Fawcett, 2010). For example, individuals with DD may exhibit both reading and syntactic impairments.

In support of this perspective, several neuroimaging studies report cerebellar impairment in individuals with dyslexia (Nicolson et al., 1999; Rae et al., 1998). Recent research has found that the right cerebellum anatomy best discriminates between normal readers and individuals with dyslexia (Pernet, Poline, Demonet, & Rousselet, 2009). Other studies have observed atypical basal ganglia activity in those with dyslexia (Brunswick, McCrory, Price, Frith, & Frith, 1999; Kita et al., 2013; Paulesu et al., 1996). Furthermore, behavioral research demonstrates impairments among individuals with DD on a variety of tasks believed to be sub-served by the procedural learning system, such as implicit learning tasks. Children and adults with DD exhibit impaired performance on common implicit learning paradigms such as the serial reaction time task (SRT; Gabay, Schiff, & Vakil, 2012c; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Pugh et al., 2014; Stoodley, Harrison, & Stein, 2006; Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003) and artificial grammar learning (AGL; Pavlidou & Williams, 2014). Furthermore, implicit motor learning skills among those with DD have been found to be more fragile, to be less resistant to interference (Gabay, Schiff, & Vakil, 2012b) and to consolidate less effectively (Gabay, Schiff, & Vakil, 2012a; Hedenius et al., 2013) compared to implicit learning among normal readers.

Several studies have found intact procedural learning in those with DD (Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006). However, a recent meta-analysis on procedural learning in DD indicates this intact procedural learning performance can arise from compensatory declarative learning mechanisms that may mask procedural learning deficits in DD (Lum et al., 2013). In support of this possibility, experiments with older participants, or studies using simple (deterministic) sequential structures are more likely to be contaminated by compensation via declarative processes during procedural learning tasks. In considering these factors in a meta-analysis of the literature, Lum et al. (2013) conclude procedural learning is impaired in DD.

Precisely how procedural learning impairments relate to the reading deficits of DD is not yet well understood. Refining the details of procedural learning specifically affected in DD remains an important research objective. As noted above, some have hypothesized that impaired procedural learning may interfere with skill automation or articulation, in turn leading to impoverished phonological representations that do not effectively support learning to read (Nicolson & Fawcett, 2011). This conceptualization emphasizes the motor and skill-acquisition functions associated with procedural learning systems (Doyon & Benali, 2005; Julien Doyon, Penhune, & Ungerleider, 2003; Ungerleider, Doyon, & Karni, 2002). Consistent with this perspective, the majority of implicit learning studies in those with DD have focused on procedural learning in the *motor* domain. This has arisen partly from efforts to examine whether procedural learning impairments in DD are general, and not specifically tied to language processing. Whereas impaired motor procedural learning in DD is consistent with theoretical claims of a general learning impairment, not specific to phonological processing or to language development (Brookes et al., 2007; Fawcett & Nicolson, 1995; Howard, Howard, Japikse, &

Eden, 2006; Lum et al., 2013; Stoodley et al., 2006; Stoodley, Ray, Jack, & Stein, 2008), the very breadth of these tasks means that the precise definition of "procedural" that is impaired in dyslexia remains underspecified (Song, 2009). In this regard, it is noteworthy that accumulating evidence implicates the procedural learning system in nonmotor behavior including learning, perceptual and linguistic processing (Middleton & Strick, 2000; Seger, 2008; Strick, Dum, & Fiez, 2009). For example, procedural learning has been implicated in sequence formation (Goschke, Friederici, Kotz, & Van Kampen, 2001), probabilistic category learning (Shohamy, Myers, Onlaor, & Gluck, 2004), and perceptual categorization (Maddox & Ashby, 2004; Seger, 2008). It has also been closely tied to formation of grammar rules (Ullman, 2001). In better understanding the nature of procedural learning impairment in dyslexia, it will be especially important to examine aspects of procedural learning that may be relevant to the language domain. This will allow us to better understand how the ubiquitous phonological deficits in DD may arise from a general procedural learning impairment.

1.4 Statistical learning

To this end, we investigate whether individuals with DD are impaired at detecting statistical regularities in the order of syllables or tones across a continuous stream of sound (Saffran et al., 1996). The classic statistical learning (SL) paradigm measures the ability to detect boundaries between groups of elements based on the sequential probabilities among the elements (Saffran, Johnson, Aslin, & Newport, 1999). In a typical SL task, participants hear a continuous acoustic stream of syllables such as *tupirogolabubidakupadoti.* Within the stream, syllables are ordered such that transitional probabilities between some pairs of syllables are higher (1.0, *la* always precedes *bu*) whereas others are lower (.33, either *ro, ku, or ti* may precede *go*). Immediately after passively listening to these acoustic streams, participants are able to distinguish between sound sequences with higher transitional probabilities and those with lower transitional probabilities (Saffran, Aslin, & Newport, 1996; Saffran et al., 1999; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997).

This sensitivity to the transitional probability between sound sequences is thought to support word segmentation in fluent speech because words would be expected to have higher transitional probabilities among syllables ("pre" regularly precedes "tty," as in "pretty") than sequences that cross word boundaries ("tyba" in the English phrase "pretty baby"). Nonetheless, sensitivity to transitional probabilities across continuous input appears to be domain general in that it is observed for non-speech tones (Saffran et al., 1999), music (Tillmann & McAdams, 2004), and visual shapes (Turk-Browne, Jungé, & Scholl, 2005) in addition to syllables.

SL is believed to be a form of implicit learning because learning proceeds in the absence of intention to learn (Perruchet & Pacton, 2006). Another criteria for implicit learning is that learning appears to be inaccessible to consciousness (Reber, 1967). However, there is a great debate about whether implicit learning tasks, including SL tasks (Turk-Browne et al., 2005), can actually occur without consciousness (Shanks, 2003).

Similar to other implicit learning tasks (such as the SRT task), SL is evident for both simple and higher order structures (Fiser & Aslin, 2001; Newport & Aslin, 2004). Moreover, neuroimaging evidence is consistent with engagement of the procedural learning system during SL tasks (Karuza et al., 2013; Turk-Browne, Scholl, Chun, & Johnson, 2009). Although both implicit learning tasks and SL tasks pursue the objective of investigating general learning mechanisms under unsupervised learning situations, there are several important differences. Whereas other implicit learning tasks (such as the serial reaction time task and artificial grammar learning tasks) are believed to rely of the *formation of chunks* (Buchner, Steffens, & Rothkegel, 1998; Pothos & Bailey, 2000), SL believed to involve *statistical computations* (Buchner et al., 1998). It is still not clear whether statistical computations and chunk formation are independent processes or whether one process is based on another (Thiessen, Kronstein, & Hufnagle, 2013). One possibility is that chunks are inferred from the results of (unconscious) statistical computations. Another possibility is that (perhaps conscious) chunks are formed from the outset and then evolve as a result of basic associative learning principles (for a review see, Perruchet & Pacton, 2006). Furthermore, in contrast with other implicit learning tasks (such as AGL tasks) SL tasks involve continuous input which has to be segmented into discrete units, thus perhaps more resembling some of the demands encountered in language acquisition. These potential differences between SL tasks and other implicit learning tasks (and, by association, procedural learning), and the potential contribution of SL to language acquisition, highlight the importance of examining SL in participants with DD.

In the present study, we examine SL among participants with DD and controls across stimulus materials created with speech syllables and with nonspeech tones. The phonological deficit account of DD is consistent with the expectation that DD listeners will perform poorly on SL tasks comprised of continuous streams of syllables because DD would reduce the accuracy with which participants perceive or encode the phonological input during familiarization. However, if individuals with DD have a general impairment that impacts procedural learning tasks more generally, then DD performance should be impaired relative to controls on both speech and nonspeech SL tasks.

We also examine the relationship between SL performance and individual reading ability. Previous research has demonstrated that reading abilities are associated with visual SL performance among typical readers (Arciuli & Simpson, 2012). Based on this, we expect to observe correlations between standardized reading tests and SL performance. We also expect that there may be correlations between SL and other reading related skills factors, such as rapid naming. According to the procedural learning hypothesis, procedural learning impairment disrupts reading by impacting automatization. As such, there should be an association between the ability to automatically associate stimuli such as letters with their appropriate names (measured by RAN tasks; Denckla & Rudel, 1976) and SL performance. Note also that this theory predicts problems in naming that are not confined to reading-related tasks. Namely, DD individuals are expected to be impaired in naming all stimulus types (e.g. colors) and not only in naming that requires grapheme-phoneme decoding (e.g., letters) (Fawcett & Nicolson, 1994). Thus, we examined whether SL abilities would be related to the ability automatically name alphanumeric materials (letters or numbers) or to rapid automatic naming of any category (such as digits, letters, objects, colors).

2. General Method

2.1 Participants

Sixteen volunteers with DD and an equal number of control volunteers participated. All were native-English university students in the area of Pittsburgh with no reported signs of sensory or neurological deficits, including attention deficit hyperactive disorder. All came from families of middle to high socioeconomic status. Diagnosis of a comorbid developmental learning disability was an exclusion criterion. A well-documented history of dyslexia was the inclusion criterion for the dyslexia group: 1) each individual received a formal diagnosis of dyslexia by a qualified psychologist; 2) each individual's diagnosis was verified by the diagnostic and therapeutic center at their university and 3) each individual was receiving accommodations in educational settings. The Control group was age matched with the DD group, with no reading problems and the same level of cognitive ability (as measured by the Raven's Standard Progressive Matrices (SPM) test; Raven, 1992). The inclusion criterion for the Control group was a lack of history of learning disabilities as well as performing at or above average on standardized measures of reading. Written informed consent was obtained from all participants. The study was approved by the Psychology Research Ethics Committee of CMU and it was conducted in accordance with the Declaration of Helsinki.

All participants underwent a series of cognitive tests (see Table I for a detailed description) to evaluate general intelligence (as measured by Raven's Progressive Matrices) verbal working memory (as measured by the forward and backward Digit Span from the Wechsler Adult Intelligence Scale, Wechsler, 1997), rapid automatized naming (Wolf & Denckla, 2005) and phonological awareness (Spoonerism). In addition, all participants performed both un-timed and timed (fluency) tests of word reading and decoding skills. Participants performed the Word Identification (WI) and Word Attack (WA) subtests from the Woodcock Reading Mastery Test-Revised (WRMT-R; Woodcock, 1987). In addition, participants performed the Sight Word Efficiency, Forms A+B (i.e., rate of word identification) and Phonemic Decoding Efficiency, Forms A+B (i.e., rate of decoding pseudo-words) subtests from the Test of Word Reading Efficiency (TOWRE-II; Torgesen, Wagner, & Rashotte, 1999). Results are shown in Table II.

DD and Control groups did not differ in age and general intelligence. However, compared to the Control group, the DD group exhibited a clear profile of reading disability conforming to the symptomatology of DD. They differed significantly from the Control group on word reading and decoding skills in both rate and accuracy measures (see Table II). In addition, the DD group showed characteristic deficits in the three major phonological domains:

phonological awareness (Spoonerisms), verbal short-term memory (digit span) and rapid naming (rapid automatized naming).

Note that all participants in the DD group were high functioning university students with dyslexia. Prior studies dyslexia reveal that such participants exhibit average performance on standardized reading tests (including that of low frequency words such as word identification from the Woodcock Reading Mastery Test- Revised) but nevertheless differ significantly from matched control groups and continue to present phonological problems that can be assessed by phonological tests such as the Spoonerism test (Wilson & Lesaux, 2001). Our dyslexic participants fit this profile. Each individual had received a former diagnosis of dyslexia by a qualified psychologist. The DD group differed significantly from the Control group in all literacy measures and exhibited phonological processing impairments (as indicted by the Spoonerism test), despite average performance on standardized tests. This profile is clearly indicative of a sample of dyslexic adults.

2.2 Materials

Speech Materials. The first aim was to examine if individuals with DD are sensitive to transitional probabilities across sequences of concatenated speech syllables. The stimulus materials were identical to those used by Saffran et al. (1996). The speech stream contained four consonants (/p/, /t/, /b/, /d/) and four vowels (/a/, /ae/, /i/, /u/) combined into 4 tri-syllabic nonsense words (TUPIRO, GOLABU, BIDAKU, PADOTI). These tri-syllabic stimuli were generated by a speech synthesizer in a monotone female voice at the rate of 270 syllables per minute, such that each syllable had an average duration of approximately 222 ms. Participants heard each of the 4 nonsense words 45 times (180 total words) in pseudorandom order over the course of two minutes of passive exposure with the stipulation that the same word never occurred twice in a row and that transitions between words occurred approximately equally often. The synthesizer produced no acoustic cues to word boundaries, resulting in a continuous stream of sounds. All syllables were produced in a monotonic 200 Hz fundamental frequency with unchanging rate of speech and no pauses between words or syllables. The only cues for word boundaries were the transitional probabilities between pairs of syllables, which were higher within nonsense words (1.0) than between nonsense words (.33).

Two “words” (TUPIRO, BIDAKU) for which transitional probabilities among pairs of syllables were high (1.0) during familiarization and 2 part-words (syllable sequences that occur across word boundaries during familiarization and therefore have lower transitional probabilities across syllables: TIGOLA, BUPADO) were used as test items. On each trial, participants heard one word test item and one part-word test item, and selected which sounded more familiar. Each word was paired with each part-word twice and the order of item presentation was counterbalanced across pairings (such that one time the word was presented first and the other time the part-word was presented first) to create 8 test items. Preliminary pilot data (N = 8) indicated that two minutes of exposure to the synthesized speech was sufficient to elicit significant learning among typically-developing university students (with no history of learning disability), as indicated by above-chance performance on the forced choice test items (M=82%).

Non-speech Materials. A second set of materials modeled the statistical structure of the speech materials, with non-linguistic tones replacing the syllables. These materials were identical to those of Saffran et al. (1999). Each syllable comprising the speech materials was replaced with a unique tone (e.g., BU = D#). Each of the four tri-syllabic nonsense words (e.g., BIDAKU) from the novel speech stream thereby was translated into a sequence of three tones (e.g., D#, F, E) with no silence between tones. The tone triads were concatenated without pauses in a pseudorandom order to generate a continuous stream. The order of the high transitional-probability, statistically-coherent “tone-words” was identical to the order of the words in the linguistic stimuli resulting in a statistical structure identical to the syllable materials.

The tones were drawn from an octave ranging between A at 440 Hz and ending with G# at 831 Hz (the 12 tones were A, 440 Hz; A#, 466 Hz; B, 494 Hz; C, 523 Hz; C#, 554 Hz; D, 587 Hz; D#, 622 Hz; E, 659 Hz; F, 698 Hz; F#, 740 Hz; G, 784 Hz; G#, 831 Hz). The tones were pure sine-waves synthesized in Adobe Audition. Based on previous research, each tone was 330 ms (Saffran et al., 1999). Note that this is slightly longer than the duration of each syllable in the speech materials; prior research suggests that adults require tonal stimuli to be presented somewhat more slowly than speech stimuli to achieve equivalent performance. As such, although participants heard the same number of “tone words” (180 total; 45 of each of the 4 triads) as in the speech materials, the overall duration of familiarization with the tone materials was longer (2 minutes and 50 seconds).

The test items were structured in the same way as the test items for the speech materials: 8 two-alternative forced choice items included both tonal words and tonal part-words. In the test phase each trial consisted of a pair of tone triads. One of which was a “tone word” from the familiarization stream with high (1.0 tone-to-tone transitional probabilities) statistical coherence. The other straddled a “tone word” boundary in the familiarization stream and had low transitional probabilities (.33) within the triad. The test items included 2 tone words (ADE and BFG) and 2 part-words (D#G#A# and F#CC#); each tone word was paired with each part-word twice, with order counterbalanced. Preliminary pilot data (N=8) suggests that the two minutes and 50 seconds of exposure to the synthesized tone stream was sufficient to elicit learning among typically-developing university students (with no history of learning disability), as indicated by above chance performance on the forced choice test items (M=82%).

2.3 Procedure

All testing took place in sound-attenuated booths with participants wearing headphones (Beyer, DT-150) while seated directly in front of a computer monitor. Stimulus presentation and the recording of response time and accuracy were controlled by a computer program (E-Prime; Schneider, Eschman, Zuccolotto, & Guide, 2002).

All participants first completed a familiarization phase during which they listened passively to a sequence of sounds. Immediately after the familiarization phase, participants completed a two-alternative forced-choice test consisting of 8 trials. Each trial consisted of a pair stimuli: one word and one part-word. Participants' task was to judge which of the two sounds was most similar to the sounds heard during familiarization by pressing "1" or "2" on the computer keyboard to indicate the first or second sound. Trial order was randomized.

Each participant completed a familiarization segment and a forced-choice test for both speech and non-speech materials. The order of the speech and non-speech tasks was counterbalanced across participants. Analyses revealed no main effects or interactions with the order in which the two tasks were performed.

3. Results

A mixed model analysis of variance (ANOVA) with Group (DD vs. Controls) as a between-subjects factor and SL Task (Speech vs. Non-speech) as a within-subject factor and accuracy across test trials as the dependent measure was conducted. Results are presented in Figure A.1. There was a main effect of group, F (1, 30) = 10.366, p=.003, η_p^2 = .256, indicating that the DD group performed significantly less accurately (M=69%) than the Control group (M=85%). There was no main effect of SL task and no interaction, $F < 1$.

Further analyses were conducted to investigate whether accuracy at test in recognizing statistically-coherent words from familiarization was above chance level (50%). Results for the speech materials are presented in Figure A.2. Single-sample two-tailed *t*-tests indicated that both groups exhibited SL at above-chance (50%) levels for speech materials. Overall, the DD group achieved 70% accuracy on test trials, $t(15)=3.35$, $p<.01$ whereas the Control group achieved 86% accuracy, $t(15)=8.85$, $P<.01$.

Results for non-speech materials are presented in Figure A.3. Single-sample two-tailed *t*-tests indicated that both DD and Control groups learned above chance level (50%). The DD group achieved 67% accuracy on test trials, $t(15)=3.44$, $p<.01$, whereas the Control group achieved 83% accuracy, $t(15)=8.27$, $p<.01$.

It is well established that participants can present performance variability during statistical learning tasks and that non-impaired participants can show learning at or below chance level. These participants are not excluded from analyses (Saffran et al., 1999; Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014), as in the above-mentioned ANOVA involving the full data set from all DD and control participants, since it is important to document this within- and between-group variability. The fact that more dyslexic than control participants exhibit learning at or below chance level strengthens the argument that DD individuals have difficulties in extracting statistical regularities. Nevertheless, we conducted an identical ANOVA excluding DD and Control participants who were at or below chance level at least in one of the two SL tasks (7 DD, 3 Control). Group differences were significant, $F(1, 20) = 4.79$, $p = .041$, $\eta_p^2 = .18$, with DD learners presenting less SL learning (M=80.1), compared with controls (M=89.07).

3.1 Relationship between statistical learning and individual reading ability

In addition to the group analysis reported above, we also examined the relationship between SL performance (accuracy across test trials) and reading ability, as measured by 4 standardized tests: (1) Word Identification (WI) and (2) Word Attack (WA) subtests from the Woodcock Reading Mastery Test-Revised (WRMT-R; Woodcock, 1987); (3) Sight Word Efficiency, Forms A+B (i.e., rate of word identification); and (4) Phonemic Decoding Efficiency, Forms A+B (i.e., rate of decoding pseudo-words) subtests from the Test of Word Reading Efficiency (TOWRE-II; Torgesen et al., 1999). This analysis was motivated by previous research examining the relationship between visual SL and individual reading ability (Arciuli & Simpson, 2012). Examination of the correlations allows us to investigate the relation between individual reading ability and SL, independent of diagnostic category. We also examined the correlation between SL performance and Rapid Automatized Naming, as the procedural learning deficit account predicts a positive correlation between learning performance and the ability to automatically form visual-verbal associations.

Results are presented in Table 3. The performance on most reading standardized tests was positively correlated with both speech and non-speech SL performance. Specifically, Phonemic Decoding (PD) efficiency score (which measures the ability to read phonetically regular pseudo words quickly and accurately) as well as the Sight Word (SW) efficiency score (which measures the ability to read real words quickly and accurately) were both correlated with speech and non-speech SL performance. Also the Word Attack score (which measures the ability to read pronounceable nonwords) was positively correlated with speech SL. Furthermore RAN scores (which measure the ability to automatically associate stimulus with their names) were positively correlated with both speech and non-speech SL performance. This association was evident for most categories and was not confined only to those require grapheme-phoneme decoding such as letters.

4. Discussion

The purpose of the present research was to examine statistical learning of transitional probabilities across speech and non-speech materials among individuals with DD. Control listeners with normal reading abilities exhibited SL comparable to that observed in previous studies (Saffran, Aslin, & Newport, 1996; Saffran et al., 1999). Their post-familiarization recognition of both statistically-coherent triads of syllables and tones was above-chance and was statistically equivalent across sound types. It should be noted that this equivalence was achieved, based on prior research (Saffran et al. 1999), via small methodological differences in the presentation rate of the speech and non-speech materials. The DD group also learned both speech and non-speech materials at above-chance levels. However, relative to Control participants, the DD group performed more poorly. DD learners were equally impaired on sequential statistical learning for both speech and non-speech materials. The fact that DD learners exhibited general impairment across stimulus types suggests that speech and non-speech materials do not represent a substantially different learning challenge for those with DD. Rather, it suggests a general impairment in extracting statistical structure from the acoustic environment. As a group, participants with DD performed above chance level on both SL tasks. This lessens the possibility that difficulties in processing linguistic/syntactic information are the driving force behind the poorer SL observed for DD individuals, compared to control participants. The above-chance performance may also suggest that procedural learning abilities in high functioning adults with DD are not absent, but impaired or less efficient, compared with normal readers. Indeed, procedural learning impairment across different paradigms typically is measured as a *degree* of performance difference relative to controls. Several studies have demonstrated impaired (rather than absent) procedural learning in high functioning adults with DD (Gabay, Vakil, Schiff, & Holt, in press; Howard et al., 2006). An underlying dysfunction of procedural learning in DD may result in difficulty in extracting regularities, thereby disrupting the typical course of reading acquisition. Without an efficient learning system that can detect statistical regularities, individuals with DD may face greater difficulty in reading that is not entirely based on explicit instruction. Future studies should explore whether longer exposure durations to statistical regularities might resolve the learning gap between the two groups. Additionally, it is important to remember that our study involves a group of high-achieving young adults with dyslexia. It may be suggested that our results are all the stronger for being clearly evident in a group of high-achieving young adults with dyslexia. Nevertheless, caution is warranted in extending these results broadly; further evidence will be necessarily to determine whether SL impairments (or even greater SL deficits, such as learning at or below chance level) will be observed in samples of dyslexics who are not high-functioning university students, such as children with dyslexia.

The equivalent degree of impairment in SL for speech syllables and non-speech tones among the present DD listeners is difficult to reconcile with theories positing that DD arises due to impairments in phonological representation or processing (Snowling, 2000). Whereas impaired phonological processing in DD may be expected to affect SL across speech materials, a more general disruption of SL across both speech and non-speech materials is problematic. However, inasmuch as SL of transitional probabilities presents an implicit learning challenge that makes demands on the procedural learning system, the common impairment across speech and non-speech materials is consistent with theories suggesting a domain general impairment in procedural learning in DD (Nicolson & Fawcett, 2009; Ullman, 2004). Indeed, previous research has shown that DD individuals are significantly impaired on a variety of implicit learning tasks that require chunk formation such as sequence learning (Gabay et al., 2012c; Howard et al., 2006; Lum et al., 2013; Stoodley et al., 2006; Stoodley et al., 2008; Vicari et al., 2005) as well as artificial grammar learning (Pavlidou & Williams, 2014). The current experiments extend those prior results with evidence that DD participants are impaired at SL, a form of implicit learning that relies upon different process such as statistical computations and is thought to be directly related to language acquisition. Further support for the procedural learning account could be pursued with tests of whether SL for non-auditory stimuli such as sequentially-presented shapes (e.g., Baldwin, Andersson, Saffran, & Meyer, 2008; Fiser & Aslin, 2002) is impaired in DD. Although studies demonstrate a positive relationship between visual SL and reading among unimpaired adult and child readers (Arciuli & Simpson, 2012), to date research has not examined visual SL abilities among individuals with DD.

The impairment of SL among participants with DD and the observed positive correlation between reading fluency and SL performance supports theoretical claims of a link between implicit learning and reading. Specifically, both speech and non-speech SL performance were positively related to phonological decoding efficiency and sight word efficiency. Note that each of these correlated measures is an estimate of reading *fluency*, not accuracy. We predict a stronger association between SL performance and fluency, compared with accuracy, measures because of the adult college-level sample of the current study. Shaywitz (1998) has suggested that over the course of development, DD readers' become more accurate but reading remains slower, effortful and non-automatic. Thus, Shaywitz (1998) argues that timed reading measures (speed) must be used for the diagnosis of DD at the level of college or professional school. Since timed reading measures are the best predictors of DD among the type of high-functioning university students with reading difficulties that we tested, the relationship of these measures to SL impairment is supporting evidence of the relationship of SL to DD. This observation could also be considered with regard to the fact that in the present data an accuracy measure (for example, the Word Attack task) was correlated only with performance on the speech SL, and not with performance on non-speech SL. It may be that fluency measures provide a finer, more sensitive assay of DD impairment among the university-level adults we tested here. This possibility should be considered with caution due to the modest sample size employed in the current study, but it informs future research.

4.1 How might atypical SL affect linguistic development?

The observation that adults with DD are less efficient at tracking transitional probabilities across acoustic elements suggests a number of possible routes to the poor language outcomes that typify DD. First, impairment in the ability to learn from statistical structure in the acoustic environment may influence lexical development directly by reducing the ability to extract word forms from fluent speech. This could lead to a smaller vocabulary, and more difficulty in processing lexical items. Given that lexical development interacts with phonological development (Stoel-Gammon, 2011), one possibility is that inefficiency in SL may result in smaller or less robust vocabularies which could impact the resolution of phonological representations. This could produce phonological processing deficits characteristic of DD. This relationship might also present in the opposite direction, with poor phonological skills impacting vocabulary development (Aguiar & Brady, 1991). Independent of the casual relation between phonological processing and vocabulary, research has demonstrated slow lexical development in children with DD (Lyytinen & Lyytinen, 2004; Scarborough, 1990). Alternatively, impaired SL might influence learning to read directly by reducing sensitivity to the statistical regularities that exist among letters and phonemes, including the discovery of phonological rules. Lastly, the acquisition of phonological categories involves two important processes. Listeners must discover functional units of language from a continuous sound stream without a priori knowledge of the temporal time window that characterized these units (Segmentation). Moreover, since the detailed acoustic of these units varies across instances as a function of a preceding context, different talkers and speech rates, listeners must generalize from highly variably experienced acoustics to new exemplars (Categorization). The current study demonstrated impairment in statistical learning that could support segmentation, which in turn could lead to problems in acquisition of phonetic categories among learners with DD. Future studies should also explore how DD learners cope with speech category learning and how it impacts the resolution of phonological representations. As we noted above, the present results are consistent with a general procedural learning impairment among individuals with DD. Since language-learning is likely to place many demands on the procedural learning system beyond segmentation of fluent acoustic streams, poor SL performance among individuals with DD may be but one of a larger constellation of impairments arising from a more general cause.

Although the present data do not definitively determine the nature of the relationship of DD and SL, they are significant in that they establish for the first time that participants with DD are poorer at extracting statistical regularities from fluent sound streams than typical readers. The fact that this impairment is general and not specific to phonological processing is of particular importance. The results are consistent with evidence that general procedural learning is impaired in those with DD and support the possibility that tracking transitional probabilities of elements within acoustic streams is related to reading competence.

4.2 Implications for domain-general vs. domain-specific debate

Statistical learning is believed to involve a domain general mechanism by which the cognitive system discovers the underlying distributional properties of the input. However, current evidence suggests that SL emerges from local computations carried out within a modality and via a multi-domain neurocognitive system that either modulates or operates on inputs from modality- specific representations (for reviews see, Conway & Pisoni, 2008; Frost, Armstrong, Siegelman, & Christiansen, 2015). As such, problems with statistical learning could stem from both modality-constrained learning processes and global, higher-order learning processes. For example, previous research has been shown that two sequences of statistical regularities can be learned simultaneously across modalities as well as within a modality, as long as vocabularies do not share the same perceptual dimensions (for example, two different sequential structures from the same modality: tone vs. non-words or visual shapes vs. color) . However, learning suffers when the two within-modality sequences share the same perceptual dimension (Conway & Christiansen, 2006).

Examination of statistical learning in reading impaired populations could inform us about the domain general versus domain specific debate. A general deficit across sensory modalities or different perceptual dimensions would be in favor of domain-general system acting upon statistical regularities. Our current investigation was not designed to empirically test this question. However, the fact that SL impairments among DD individuals were not confined to speech materials implies an impairment affecting domain-general learning processes. Targeted research examining SL among impaired readers for sequences within and across modalities with perceptual dimensions that are orthogonal or overlapping will be informative in relating how domain-general deficits may affect language and reading development.

5. References

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Acknowledgements

The authors declare that they have no conflict of interest. This work was supported by a grant to L.L.H. from the National Institutes of Health (R01DC004674).

Tables

Table I – Psychometric Tests

The following tests were administered according to the test manual instructions:

1. *Raven's Standard Progressive Matrices test* (Raven, Court & Raven, 1992) – Non-verbal intelligence was assessed by the Raven's-SPM test. This task requires participants to choose the item from the bottom of the figure that would complete the pattern at the top. The maximum raw score is 60. Test reliability coefficient is .9

2. *Digit Span from the Wechsler Adult Intelligence Scale* (WAIS-III; Wechsler, 1997) - In this task participants are required to recall the names of the digits presented auditorily in the order they appeared with a maximum of total raw score 28. Task administration is discontinued after a failure to recall two trials with a similar length of digits. Test reliability coefficient is .9

3. *Rapid Automatized Naming* (Wolf & Denckla, 2005) - The tasks require oral naming of rows of visually-presented exemplars drawn from a constant category (RAN colors, RAN categories, RAN numerals, and RAN letters). It requires not only the retrieval of a familiar phonological code for each stimulus, but also coordination of phonological and visual (color) or orthographic (alphanumeric) information quickly in time. The reliability coefficient of these tests ranging between .98 to .99.

4. *Woodcock Reading Mastery Test Word Identification and Word Attack subtests* (Woodcock, 1987). The Word Identification subtest measures participants' ability to accurately pronounce printed English words, ranging from high to low frequency of word occurrence with a maximum of total raw score 106. Test reliability coefficient is .97. The Word Attack subtest assesses participants' ability to read pronounceable nonwords varying in complexity with a maximum total raw score of 45. Test reliability coefficient is .87. Task administration is discontinued when 6 consecutive words are read incorrectly.

5. *Sight Word Efficiency* (i.e., rate of word identification) and *Phonemic Decoding Efficiency*, (i.e., rate of decoding pseudowords) subtests from the Test of Word Reading Efficiency (TOWRE-II; Torgesen et al., 1999) were used to measure reading rate. The test contains two timed measures of real word reading and pseudo word decoding. Participants are required to read the words aloud as quickly and accurately as possible. The score reflects the total number of words/nonwords read correctly in a fixed 45-s interval. Task administration is discontinued after 45 seconds. Sight word efficiency maximum raw score is 108. Phonemic decoding efficiency maximum raw core is 65. Test-retest reliability coefficients for these subtests are .91 and .90 respectively.

6. *Spoonerism Test* (adapted from Brunswick et al., 1999) - This test assesses the participants' ability to segment single syllable words and then to synthesize the segments to provide new words. For example, the word pair "Basket Lemon" become "Lasket Bemon". The maximum raw score is 12.

Table II- Demographic and Psychometric Data of Dyslexia and Control Groups

Measure	Group					
	Dyslexia *Mean (SD)*	Range	Control *Mean (SD)*	Range	*P*	Cohen's *d*
Age (in years)	21.56 (4.89)	18-35	22.12 (2.94)	18-30	*n.s.*	.13
Raven's SPM	56.93 (2.9)	51-60	58 (2.3)	52-60	*n.s.*	.4
DS[a] (combined)	10.25 (2.86)	5-16	13.68 (2.44)	8-18	*<.01*	1.29
RAN objects[a]	103.87 (19.12)	74-129	117.81 (10.13)	100-133	*<.05*	.91
RAN colors[a]	98.31 (13.74)	80-124	112.75 (5.11)	103-121	*<.01*	1.39
RAN numbers[a]	106.12 (5.4)	95-113	114 (3.91)	107-120	*<.01*	1.67
RAN letters[a]	102.56 (6.1)	85-111	111.93 (4.95)	102-117	*<.01*	1.808
WRMT-R WI[a]	98.37 (5.004)	92-113	111.18 (7.74)	100-126	*<.01*	1.96
WRMT-R WA[a]	96 (8.73)	82-115	115 (12.07)	100-137	*<.01*	1.803
TOWRE SA (A+B) [a]	97.31 (8.2)	81-112	114.94 (8.82)	100-127	*<.01*	2.07
TOWRE PD (A+B) [a]	90 (9.12)	72-112	114.37 (9.94)	100-127	*<.01*	2.55
Spoonerism time	148.43 (71.67)	82-368	92.93 (30.5)	63-150	*<.01*	1.007
Spoonerism accuracy	8.12 (3.66)	1-12	11 (2.21)	4-12	*<.05*	.95

Note. SPM = Raven's standard Progressive Matrices; RAN = Rapid Automatized Naming; DG = Digit Span subtest from the Wechsler Adult Intelligence Scale; WRMT-R WI = Woodcock Reading Mastery Test – Word Identification; WRMT-R WA = Woodcock Reading Mastery Test – Word Attack; TOWRE-II – Test of Word Reading Efficiency.

[a]Standard scores (whereby smaller numbers are expected for dyslexic group), other scores are raw scores.

Table III - Correlation coefficients between Speech and Non-Speech SL Performance of the DD and Control groups and Psychometric Tests.

Measurement	**Speech SL**	**Non-Speech SL**
Standardized reading tests		
WRMT-R WI	.193	.281
WRMT-R WA	.420**	.243
TOWRE SA (A+B)	.370*	.355*
TOWRE PD (A+B)	.511**	.306*
Rapid naming		
RAN objects	.221	.397*
Ran colors	.439*	.345*
RAN numbers	.394*	.358*
RAN letters	.324*	.306*
Phonological awareness		
Spoonerism time	-.285	-.166
Spoonerism accuracy	.340*	.054
Verbal Working Memory		
DG	.261	.240
Cognitive ability		
Raven's SPM	-.147	.037

Note. SPM = Raven's standard Progressive Matrices; RAN = Rapid Automatized Naming; DG = Digit Span subtest from the Wechsler Adult Intelligence Scale; WRMT-R WI = Woodcock Reading Mastery Test – Word Identification; WRMT-R WA = Woodcock Reading Mastery Test – Word Attack; TOWRE-II – Test of Word Reading Efficiency.

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

Figure captions

Figure A.1*:* Average test trial accuracy of DD and Control groups after familiarization with speech and non-speech sequences. Error bars represent standard errors.

Figure A.2: A scatterplot of test trial accuracy of the DD and Control participants on the speech task.

Figure A.3: A scatterplot of test trial accuracy of the DD and Control participants on the non-speech task.

Figure A.1

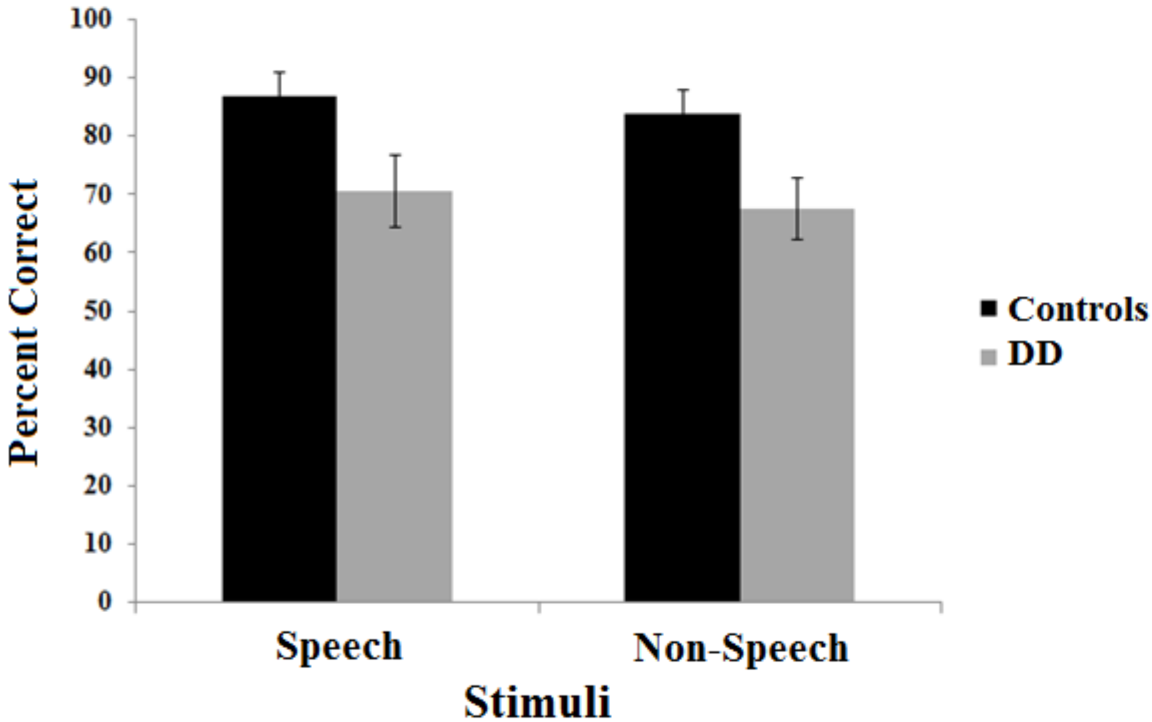


Figure A.2

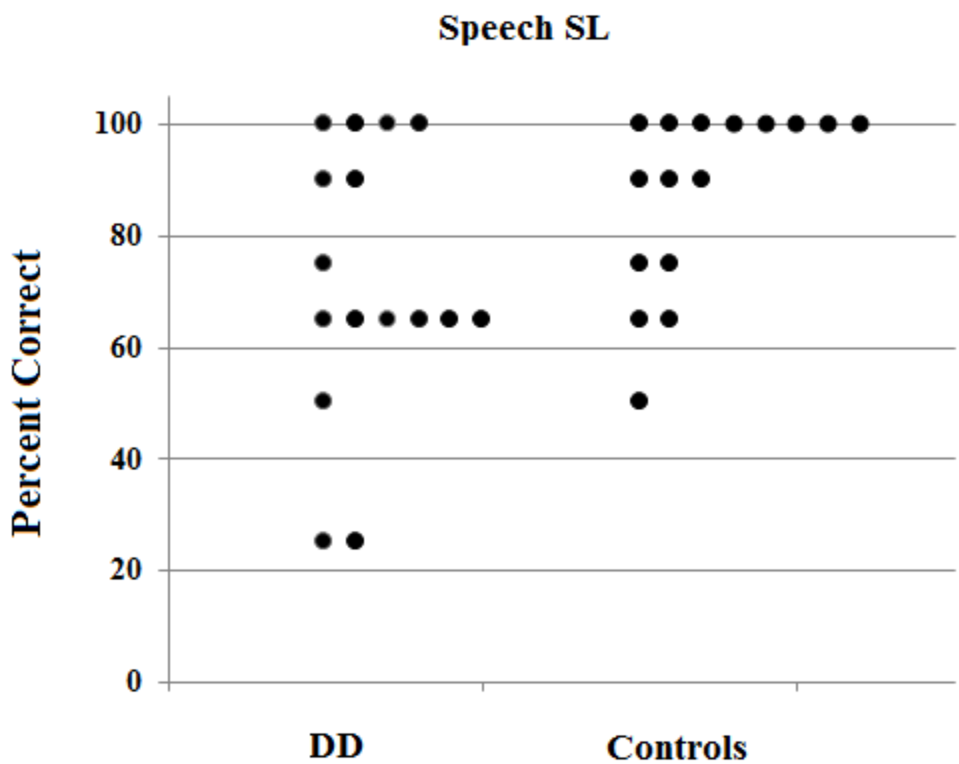
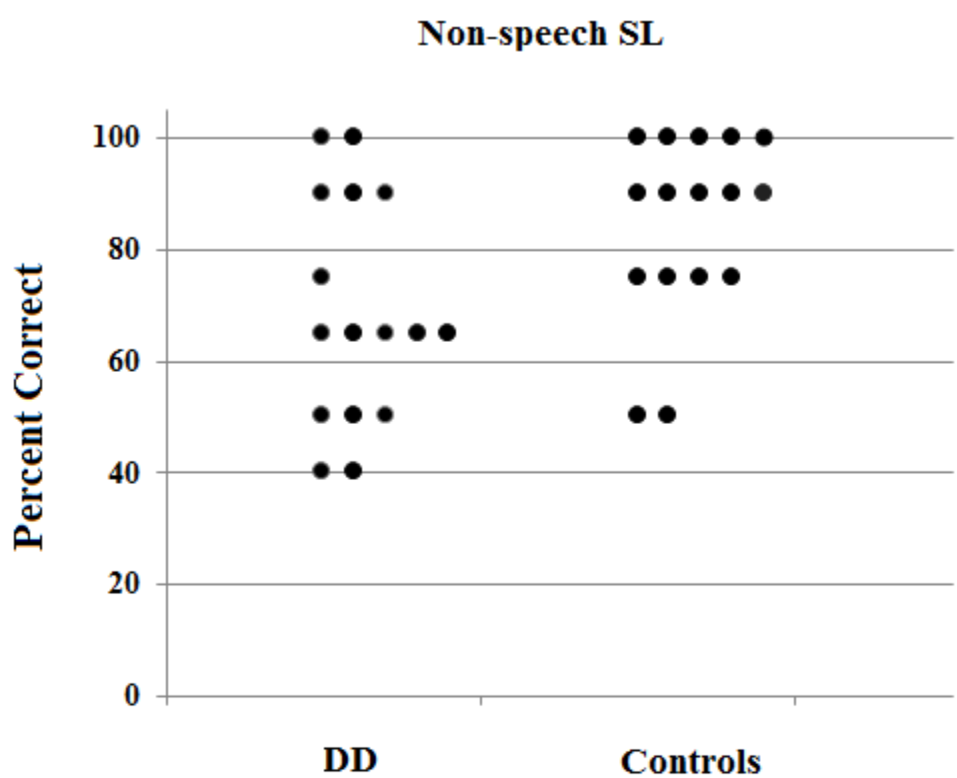


Figure A.3


Non-speech SL
Percent Correct
100
80
60
40
20
0
DD
Controls