The Perception of “Sine-Wave Speech” by Adults With Developmental Dyslexia

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Numerous studies have shown that, as a group, children or adults with developmental dyslexia perceive isolated syllables or words abnormally. Continuous speech containing reduced acoustic information also might prove perceptually difficult to such listeners. They might, however, exploit the intact syntactic and semantic features present in whole utterances, thereby compensating fully for impaired speech perception. “Sine-wave speech” sentences afford a test of these competing possibilities. The sentences contain only 4 frequency-modulated sine waves, lacking many acoustic cues present in natural speech. Adults with and without dyslexia were asked to orally reproduce 9 sine-wave utterances, each occurring in 4 immediately successive trials. Participants with dyslexia reported fewer words than did control listeners. Practice, phonological contrasts, and word position affected both groups similarly. Comprehension of sine-wave sentences seems impaired in many, but not all, adults with dyslexia. A reduced auditory memory capacity may contribute to this deficit.

KEY WORDS: speech perception, sine-wave speech, dyslexia, memory

Poor phonological skills are recognized as an immediate cause of the reading deficits in developmental dyslexia (Goswami & Bryant, 1990; Wagner & Torgeson, 1987). Numerous speech perception experiments have explored receptive aspects of those phonological impairments. The results show that children and adults with dyslexia manifest various deficits in the identification and discrimination of speech sounds. These experiments, however, have used isolated syllables or words. This limitation raises the question of whether children or adults with dyslexia would still be impaired in understanding continuous speech, particularly when acoustic cues are impoverished. Such utterances would still retain normal syntactic and semantic information. Listeners with dyslexia might compensate fully for lower level deficits in speech perception by exploiting such higher order information in continuous speech with reduced acoustic cues. We examine this possibility here.

Previous identification studies with children as participants have used synthetic stop consonants varying in voicing (Dreier et al., 2001; Chiappe, Chiappe, & Siegel, 2001; DeWeerdt, 1988; Manis et al., 1997) or in place of articulation (Aldard & Hazan, 1998; Brandt & Rosen, 1980; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Reed, 1989, Rosen & Manganari, 2001; Werker & Tees, 1987). A /set/-/ste/' synthetic series (Mody, Studdert-Kennedy, & Brady, 1997) and a /su/-/zu/ continuum (Aldard & Hazan, 1998) have also been employed. Reed’s (1989) findings with a
nine-stimulus synthetic /ba/-/da/ continuum are typical. Children with reading impairments produced flatter average identification functions than did control children. As in all other studies, however, some poor readers yielded normal identification functions, whereas others displayed varying degrees of abnormality. (Brandt & Rosen, 1980, found no such differences.) Poor readers also proved less proficient than normal readers at identifying isolated monosyllabic words in a masking noise, failing on words with stops at a relatively high rate (Brady, Shankweiler, & Mann, 1983). Identification of masked environmental sounds yielded no group difference, suggesting an impairment specific to speech.

Some children with dyslexia show impaired discrimination of natural tokens of stops, fricatives, nasals, and approximates (Aldard & Hazan, 1998; Hurford & Sanders, 1990; Masterson, Hazan, & Wijayatilake, 1995). Sernicaaes, Sprenger-Charolles, Carré, and Demonet (2001), however, found the opposite effect with six “sine-wave speech” syllables (see Remez, Rubin, Pisoni, & Carroll, 1981). Each syllable contained just three sine waves that tracked the center frequencies of the first three formants of a synthetic /ba/-/da/ stimulus. Appropriate instructions can induce most listeners to hear the stimuli either as nonspeech whistles or as speech. Children who read poorly were more accurate than control listeners in discriminating between nearby sine-wave stimuli located at either end of the continuum, especially when instructed to listen for speech. Godfrey et al. (1981) and Werker and Tés (1987) had reported similar results with conventional synthetic speech stimuli. Sernicaaes et al. concluded that poor readers were “less categorical” in speech perception than were normal readers. Kraus et al. (1996), however, found that children with learning problems, including dyslexia, discriminated stimuli around the endpoints of /da/-/ga/ and /ba/-/wa/ continua more poorly than did control children. Compared to the control children, these children also showed reduced electrophysiological mismatch responses to the stimuli. Furthermore, Rosen and Manganari (2001) reported that children with dyslexia discriminated between synthetic stops more poorly than did control listeners; Reed (1989) noted weak evidence along these lines; Brandt and Rosen (1980) observed no differences at all.

In summary, children who read poorly tend to show flatter speech identification functions than do control children. Differences in speech discrimination also have been reported between these two types of children, but the data conflict on the direction of the difference.

Phonological deficits in dyslexia can persist well beyond childhood (e.g., Pennington, Van Orden, Smith, Green, & Haith, 1990). Accordingly, some adults diagnosed as having dyslexia were impaired at identifying synthetic steady state vowels and natural voiced stops that varied in place of articulation (Lieberman, Meskill, Chatillon, & Schupack, 1985). Cornelissen, Hansen, Bradley, and Stein (1996) obtained identifications of isolated natural CV syllables in noise (see Miller & Nicely, 1955). Adults with dyslexia performed below the level of control listeners, tending particularly to confuse different fricatives. Finally, Steffens, Eilers, Gross-Glenn, and Jallad (1992) found flattened identification functions for synthetic /ba/-/da/ and /spa/-/sa/ continua in adult males and females with dyslexia. The male subgroup even showed this effect with a vocalic /al/-/a/ continuum. As a group, however, listeners with dyslexia showed virtually no differences in vowel discrimination. In short, adults with developmental dyslexia, like children who read poorly, show deficits in identification of isolated syllables. No reductions in speech discrimination, however, have been reported for such adults.

All the experiments reviewed above used isolated syllables or words. The findings suggest that listeners with dyslexia should have trouble following continuous speech that is acoustically impoverished. The opposite, however, is also a possibility. Adults with dyslexia apparently understand natural speech during lectures, the presentation of experimental instructions, and conversation. Moreover, they can reproduce spoken sentences as well as control participants, even when the sentences have been broken into successive 25-ms segments and each segment reversed in time (Witton et al., 1999; for the reverse windowing procedure, see Saberi & Perrott, 1999). Acoustically impoverished continuous speech would still retain the syntactic and semantic information found in natural utterances. By exploiting that information, adults with dyslexia might fully compensate for deficits in speech perception. Therefore, they might perform as well as control listeners in following continuous speech with reduced acoustic cues.

To test these two conflicting possibilities, we examined the ability of adults with and without developmental dyslexia to repeat sine-wave speech sentences. A sine-wave utterance contains three frequency-modulated sinusoids that trace out the center frequencies of the first three formants of its natural counterpart (Remez et al., 1981; Remez, Rubin, Berns, Pardo, & Lang, 1994). A fourth sine wave tracks the center frequency of any fricative resonance. All center frequencies are estimated by linear prediction. The amplitude envelope of the model utterance is imposed on the time-domain algebraic sum of the four sinusoids. The resulting synthetic stimulus is spectrally impoverished and lacks the aspiration and frication noises that are important consonantal cues in natural speech. Sine-wave speech nevertheless preserves information about the changing vocal tract configurations that generate the sounds of natural speech.
Remez et al. (1981) found that most (but not all) adult listeners understood sine-wave sentences to some degree, when instructed to transcribe computer-generated speech. After eight successive exposures to binaurally presented sine-wave sentences, listeners (presumably without dyslexia) had, on average, correctly transcribed about 70% of the syllables (Remez et al., 1994). These previous findings provided a baseline for our study and motivated our use of adult participants. Similar baseline data do not exist for stimuli such as continuous speech in noise.

Our main purpose, then, was to determine whether the semantic and syntactic cues present in continuous sine-wave speech would permit adults with developmental dyslexia to perform as well as controls. This carries the study of speech perception in developmental dyslexia beyond the previous work on isolated syllables or words.

Method

Participants

Nineteen adults with previous diagnoses of dyslexia (N = 10 males, 9 females; mean age = 27.9 years, SD = 10.4) and 14 adults without dyslexia (N = 3 males, 11 females; mean age = 27.7 years, SD = 9.6) participated in this study. The listeners with dyslexia were recruited through support groups at two local universities. The participants without dyslexia came from the same universities and had equivalent levels of educational experience. All participants were unpaid volunteers and were naive to sine-wave speech. They reported no neurological problems and no hearing difficulties. In conjunction with another experiment conducted at the same time as ours, 8 of our participants with dyslexia and 8 of our listeners without dyslexia underwent a screening test for absolute threshold at 1 kHz. All 16 of these listeners gave results within 10 dB of hearing level.

Educational psychologists had positively diagnosed all participants with dyslexia within the past 5 years, using the conventional criterion, among others, of a significant discrepancy between literacy and other cognitive skills. No listener without dyslexia reported any personal or family history of reading problems. Within several weeks of the test on sine-wave speech, each participant also completed the single-word Reading and Spelling subtests from the revised Wide-Range Achievement Test Revised (WRAT-R; Jastak & Wilkinson, 1984) and the Digit Span, Block Design, and Picture Arrangement subscales of the Wechsler Adult Intelligence Scale—Revised (WAIS-R; Wechsler, 1991). The WRAT-R scores were restandardized to a mean of 10 and a standard deviation of 3. A discrepancy score (D) between cognitive and literacy skills was then calculated in standard deviation units. This Z-score measure is one third the difference between the average of Block Design (WAIS-R-BD) and Picture Arrangement (WAIS-R-PA) and the average of the reading (WRAT-R-R) and spelling (WRAT-R-S) scores. Thus, D = ((WAIS-R-BD + WAIS-R-PA)/2 - (WRAT-R-R + WRAT-R-S)/2)/3.

Table 1 contains the psychometric data. Exact, two-tailed Mann-Whitney tests showed that the group with dyslexia scored significantly lower than the group without dyslexia on Reading (U = 17.5, p < .001) and Spelling (U = 16.0, p < .001). The former group also had a lower WAIS-R Digit Span score than did the latter (U = 22.5, p = .001). No group differences appeared on the nonverbal Block Design and Picture Arrangement subtests of the WAIS-R. The mean discrepancy score D was 1.37 (SD = 0.97) for the listeners with dyslexia and 0.07 (SD = 0.46) for the group without dyslexia; the difference was significant (U = 27, p < .001). Five adults with dyslexia, however, had D scores below 1.0. Such scores would not justify a diagnosis of developmental dyslexia under some current criteria.

Stimuli

The stimuli were nine sine-wave utterances available as .WAV files from the Haskins Laboratories (http://www.yale.haskins.edu/haskins/MISC/SWS/SWS.html). The sentences had been modeled after natural productions from a male speaker of American English. Our British listeners were thoroughly familiar with American English after years of intensive exposure to American television programs and films and especially to American popular music. The nine sine-wave utterances are representative of a larger set used in transcription tests. After five successive exposures of each utterance.

Table 1. Psychometric scores for participants with and without dyslexia.

<table>
<thead>
<tr>
<th></th>
<th>Participants</th>
<th>With dyslexia (n = 19)</th>
<th>Without dyslexia (n = 14)</th>
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<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>WRAT-R Reading</td>
<td>9.0</td>
<td>2.0</td>
<td>13.5</td>
</tr>
<tr>
<td>WRAT-R Spelling</td>
<td>7.8</td>
<td>3.4</td>
<td>13.7</td>
</tr>
<tr>
<td>WAIS-R Digit Span</td>
<td>0.0</td>
<td>2.1</td>
<td>12.2</td>
</tr>
<tr>
<td>WAIS-R Block Design</td>
<td>13.6</td>
<td>3.6</td>
<td>14.9</td>
</tr>
<tr>
<td>WAIS-R Picture Arrangement</td>
<td>11.4</td>
<td>2.8</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Note: WRAT-R = Wide-Range Achievement Test—Revised; WAIS-R = Wechsler Adult Intelligence Scale—Revised. Scores on all five tests have been standardized to a mean of 10 and a standard deviation of 3.
in that set, listeners had correctly transcribed 65% of the words (R. E. Remez, personal communication, February 21, 2002).

Each sine-wave stimulus is designated by a letter, A through I, followed by a digit giving the number of words in the utterance. The utterances were "I read a book today." (A5); "Where were you a year ago?" (B6); "Please say what this word is." (C6); "My dog Bingo ran around the wall." (D7); "Kick the ball straight and follow through." (E7); "Rice is often served in round bowls." (F7); "My TV has a twelve-inch screen." (G7); "The beauty of the view stunned the young boy." (H9); and "The steady drip is worse than a drenching rain." (I9). Utterance durations ranged from 1.58 s (A5) to 3.28 s (H9).

Procedure

All participants were instructed that they would hear speech generated by a computer. Following Remez et al. (1981), each listener received four successive exposures to each sine-wave stimulus. The listener was asked to repeat back what had been heard, in whole or in part and as accurately as possible, after each presentation.

Stimuli were presented at approximately 65 dB SPL through binaural headphones. Each listener individually participated in a 15-min experimental session in a quiet room. A personal computer controlled the stimulus presentation, using custom software. The experimenter initiated each presentation when the participant indicated readiness. Immediately after hearing a sine-wave utterance, the listener tried to repeat it. The experimenter marked each correctly repeated word and noted any errors of commission.

The order of the nine utterances was varied systematically across the members of each of the two experimental groups. Each utterance occupied each position in the order with nearly equal probability. The probability that sentence $i$ ($i = 1, ..., 9$) immediately preceded sentence $j$ ($j 
eq i$) was kept as constant as possible across all values of $i$ and $j$.

Results

Errors in the perception of sine-wave speech were almost always omissions; some words simply failed to be reported at all. Word substitutions were very infrequent; reversals in word order within an utterance never occurred. Our basic perceptual datum, therefore, is the proportion of words correctly repeated, $P(C)$.

Some analyses of the data used general linear models. Exact nonparametric tests were used for detailed comparisons. Interrelations between dependent variables made Bonferroni corrections inappropriate, as these assume independent samples. Given the large number of statistical tests, we set $\alpha$ at a moderately conservative .025. We quote effect size ($\eta^2$) values for $F$ tests that reach significance ($p \leq .025$) but not for marginally significant tests ($0.025 < p < .05$). The base for $\eta^2$ was total variability.

Statistical analyses with mixed-factor analyses of variance (ANOVA's) required an arcsine transform on $P(C)$. To check that the data met the assumptions required by an ANOVA, we computed Box's test for equality of covariance matrices, Mauchly's test of sphericity, and Levene's test for homogeneity of variances. Hays (1994, pp. 571–577) briefly discussed these procedures; Maxwell and Delaney (1990, chapter 11) offered greater coverage. Unless stated otherwise, each test yielded a satisfactory result or, in the case of Box's test, could not be computed. When the assumption of sphericity was rejected, Greenhouse–Geisser noninteger degrees of freedom were used. Their appearance as arguments of $F$ indicates such rejection.

Sine-Wave Speech Perception: Overall Results

For each participant and each trial, we calculated total $P(C)$ across all nine utterances. Figure 1 presents box plots of the results. As a group, the adults with dyslexia seemed to perform below the level of the group without dyslexia. On each trial, however, 4 listeners with dyslexia reached or surpassed the median of the control group. Two of those 4 listeners had discrepancy scores below 1.0. Two or 3 participants without dyslexia gave $P(C)$ values below the median of the group with dyslexia. Not surprisingly, detailed inspection of the data showed that both groups found longer utterances generally more difficult to repeat than shorter ones.

An ANOVA on the arcsine-transformed data had group as a between-subjects factor and trial as a within-subjects factor. The effects of trial, $F(1, 77, 54.94) = 37.93, p < .01, \eta^2 = .32$, and group, $F(1, 31) = 6.96, p < .025, \eta^2 = .18$, were significant. The interaction was not, $F(1, 77, 54.94) = 3.18, p > .05$. Marginal means confirmed that performance improved across the four trials and that listeners with dyslexia scored consistently lower than participants without dyslexia. For each successive trial, exact Mann–Whitney tests showed a significant group difference ($U = 70.0, 69.5, 68.5, 69.5, 68.5, 69.5$ and $69.5$, respectively; $p < .025$ in each case).

We conducted Monte Carlo Mann–Whitney tests (100,000 iterations) on total $P(C)$ for each trial, comparing participants with and without hearing screening (see Method) within each of our two groups. None of the resulting eight tests were significant. Therefore, we have used the data from the entire sample of adults diagnosed as having dyslexia.
Digit Span and Discrepancy Scores

The group with dyslexia had a shorter digit span than the group without dyslexia (see Table 1). The capacity of phonological memory affects the serial recall of spoken, unrelated items. It might likewise affect the reproduction of spoken sentences. Digit span therefore might correlate positively with performance on sine-wave speech. Performance might also improve as discrepancy scores diminish among the participants with dyslexia, yielding a negative correlation. Spearman correlation coefficients (ρ) were therefore calculated between P(C) for each trial and the digit span and the discrepancy scores, respectively, within each group of listeners and across the two groups combined.

The group with dyslexia yielded a significant positive correlation between digit span and sine-wave speech comprehension on every trial (ρ = .66, .62, .67, and .66, p < .01, for Trials 1–4, respectively). No significant correlations appeared for the group without dyslexia. The significant correlations across all listeners combined (ρ = .51, .54, .57, and .57, p < .01, for Trials 1–4, respectively) were due entirely to the performance of participants with dyslexia. Their values for ρ exceeded those found for the combined groups. The results for the controls without dyslexia were not due to restricted variances. The two groups of participants had equal variances on digit span (see Table 1), and Figure 1 shows no obvious difference between the groups in interquartile ranges. After an arcsine transform on P(C), the participants without dyslexia had larger variances on each trial than did those with dyslexia, causing further computations to be deemed unnecessary.

The discrepancy scores within each group of participants never correlated significantly with sine-wave speech comprehension. For the combined groups, the correlations were −.32, −.35, −.37, and −.36 for Trials 1–4, respectively. The last three values are marginally significant at the .05 level.

Phonological Analysis

We conducted phonological analyses of errors like those done by Brady et al. (1987). To study any effects of
stops and fricatives on sine-wave speech comprehension, we compiled three sets of words across the nine sine-wave utterances. Manner of articulation was the defining feature. The purely vocalic words a and I never contributed to any sets, leaving 58 words for possible use. Elision of these words, however, contained both stops and fricatives (e.g., *stunned*) or affricates (e.g., *inch*) and could not be used in this analysis. (We follow Laver, 1994, pp. 368–373, in treating affricates as biocentonic; English affricates consist of a stop followed by a fricative.)

The three resulting sets were 19 words with fricatives and no stops, 17 words with stops and no fricatives, and 11 words with neither stops nor fricatives. The sets are represented as [F\~S\~F], [S\~F\~S], and [~S~F~F], respectively, where F and S denote fricatives and stops, | denotes a set, \~ denotes negation, and \~ denotes logical “and.”

Aldard and Hazan (1998) had reported that a subgroup of poor readers had difficulties in discriminating between natural syllables containing nasals and others without nasals. This suggested that a significant interaction might occur between reading status and the nasal/non-nasal context in sine-wave speech. Among the 58 sine-wave speech words that contained consonants, nasals occurred in 16, forming the set [N]. Ten (62%) members of [N] also had stops, fricatives, or affricates.

We computed P(C) for each trial, each participant, and each phonological set. Figure 2 displays box plots of the results for the listeners with and without dyslexia on the first and the fourth trials. The top panel shows the results for the [S\~F\~F], [F\~S\~S], and [~S~F~F] sets. The bottom panel contains the results for the [N], [S\~F\~F], and [~S~F~F] sets. Improvement over trials is evident for both groups in all five cases. Words with stops and no fricatives and words with fricatives and no stops were repeated less accurately than words lacking both stops and fricatives (Figure 2A). Words with nasals seemed to cause more difficulties than words with no nasals (Figure 2B).

We performed an ANOVA on the arcsine-transformed P(C) values for the sets [S\~F\~F], [F\~S\~S], and [~S~F~F]. Trial and phonological set were within-subjects factors; group was the sole between-subjects factor. None of the 12 Levene tests for homogeneity of variances reached significance. Trial, F(2, 27, 70, 36) = 55.00, p < .001, η² = .64; phonological set, F(1, 41, 43, 72) = 62.55, p < .001, η² = .67; and group, F(1, 31) = 6.43, p < .025, η² = .17, yielded significant main effects. Marginal means confirmed that performance improved over trials, and that differences between sets suggested by Figure 2, and showed that the participants with dyslexia performed more poorly than participants without dyslexia. There was no Class × Group interaction, F(1, 41, 43, 72) = 0.394, p > .025. For each of the three phonological sets, the adults with dyslexia simply reported fewer words than did adults without dyslexia. Significant interactions occurred, however, for Trial × Class, F(2, 25, 69, 72) = 5.20, p < .01, η² = .14, and for Trial × Class × Group, F(2, 25, 69, 72) = 4.56, p < .025, η² = .13.

Tukey tests were conducted separately on the marginal means for Trial × Class within each group of participants, because numbers were unequal between groups. A repeated-measures ANOVA provided the appropriate interaction table and error mean square for each group. On all four trials, participants with dyslexia showed significant differences (p < .01) between the [S\~F\~F] and the [~S~F~F] sets and between the [F\~S\~S] and the [~S~F~F] sets. There were no differences between the [S\~F\~F] and the [F\~S\~F] sets. In contrast, the group without dyslexia produced significant differences between the [F\~S\~S] and the [~S~F~F] sets on only the first two trials and a significant difference between the [S\~F\~F] and the [~S~F~F] sets on the second trial. No differences were significant on the last two trials. These results explain the significant interactions for Trial × Class and Trial × Class × Group found in the first ANOVA.

A separate ANOVA was conducted for the [N] and [~N] sets, with trial as a second within-subjects variable, and group as a between-subjects variable. Trial, F(1, 72, 53, 42) = 59.48, p < .01, η² = .66, and phonological set, F(1, 31) = 98.04, p < .01, η² = .76, were significant, as was the Trial × Class interaction, F(1, 91, 59.14) = 9.41, p < .01, η² = .23. Marginal means showed that performance improved over trials and that words with nasals were more difficult than those without nasals. The interaction was due to greater and earlier gains on the latter words. The listeners with dyslexia performed more poorly than those without dyslexia, F(1, 31) = 6.69, p < .025, η² = .18. There were no significant interactions involving group as a factor.

In the sets [S\~F\~F], [F\~S\~S], and [~S~F~F], 18%, 10%, and 54% of words, respectively, had nasals. Therefore, the lower P(C) for the sets [S\~F\~F] or [F\~S\~S], in comparison to the set [~S~F~F], could not reflect a confounding effect of nasals. The set [~S~F~F] had a higher proportion of nasals than did the other two sets. Likewise, in the set [N], 10 words (68%) contained stops, fricatives, or affricates, but so did 37 (88%) of the 42 words in the set [~N]. Accordingly, the lower P(C) for the set [N] as against the set [~N] could not be due to a confounding effect of affricates, stops, and fricatives. The set [~N] had a higher proportion of affricates, stops, and fricatives than did the set [N].

**Word Position Effects**

We investigated the influence of word position by computing P(C) as a function of position in each utterance of length seven (D7, E7, F7, and G7). For each
Figure 2. Box plots of P(C) for participants with dyslexia and control participants as a function of phonological sets. Markers coincide with those explained in Figure 1, and a missing lower whisker or median indicates a positively skewed sample. Each panel shows results for first, third, and fourth trials. A: Words with stops and no fricatives (S~F), words with fricatives and no stops (F~S), and words with no stops and no fricatives (~S~F). B: Words with nasals (N) and words with no nasals (~N).

After applying the transform arcsine($P(C)$)**0.8, a mixed-factors ANOVA had trial and position (7 levels) as within-subject factors; group was a between-subjects factor. Just 4 Levene tests out of 28 were significant ($p < .025$). Trial, $F(1.56, 48.48) = 23.78, p < .01, \eta^2 = .43$; position, $F(3.50, 108.34) = 13.02, p < .01, \eta^2 = .30$; and group, $F(1, 31) = 6.04, p < .025, \eta^2 = .16$, were significant factors. No interactions, including that between position and group, $F(3.50, 108.34) = 1.06$, reached significance. Marginal means indicated that words in the fifth position were reported less frequently than the first two words or the final word.

Post hoc Tukey tests were conducted separately on the marginal means for Trial × Position within each group of participants separately, in the same manner as was done above with the marginal means for Trial × Class. For the participants without dyslexia, the tests showed that $P(C)$ on the second trial was higher for
words in the second position than in the fourth or fifth positions. On the last two trials, that pattern recurred, and words in the seventh position also proved easier than words in the fifth position. For the listeners with dyslexia, the Tukey tests showed that words in the second position on the last two trials had a higher $P(C)$ than those in the fifth position. On the last trial, words in the second position were also easier than words in the fourth position. Unlike the participants without dyslexia, then, those with dyslexia ultimately showed no advantage for the final word over the fifth word in a seven-word utterance. Exact Mann–Whitney tests on the data in Figure 3 confirmed that observation. The only significant differences between groups occurred for the fifth word on the first trial ($Z = 2.97$, $p < .01$) and the seventh word on the last trial ($Z = 2.34$, $p < .025$).

**Discussion**

Adults with developmental dyslexia were consistently less proficient than adults without dyslexia at comprehending sine-wave speech utterances. A sine-wave sentence, despite its reduced acoustic cues, still has normal syntax and semantics. These intact properties, however, did not enable listeners with dyslexia, as a group, to perform at control levels.

Given this result, the motor theory of speech perception (Liberman & Mattingly, 1985) would suggest that listeners with dyslexia who have difficulties with sine-wave speech suffer from impairments in high-level articulatory mechanisms. Yet our findings are equally in accord with the proposal that speech activates specialized auditory-phonetic mechanisms that operate only...
on linguistic input (Rosner & Pickering, 1994). Those mechanisms would be impaired in listeners with dyslexia. (The two theories are not incompatible, unless one is held to be a complete account of speech perception.)

By the end of four exposures to the sine-wave utterances, our participants without dyslexia correctly reported about 65% of the words, on average. This result virtually duplicates previous findings from the Haskins Laboratories (see the Method section and Remez et al., 1994). In turn, this agreement strongly suggests that our British listeners had no difficulty understanding the sine-wave utterances, despite the fact that those sentences had been modeled on American English.

Overlap Between Listeners With Dyslexia and Control Listeners in Speech Perception

Listeners with and without dyslexia overlap on all speech perception tasks studied so far, including comprehension of sine-wave sentences. Some listeners with dyslexia even perform at or above the control group average, and some listeners without dyslexia perform no better than the average listener with dyslexia. Overlap is typical, although the overlap between groups shown in this study (see Figure 1) seems less than that described in previous studies on the perception of isolated syllables or words by children or adults who read poorly.

Bishop, Carlton, Deeks, and Bishop (1999) reported that some children with specific language impairment performed as well as the average child without such impairment on each of several auditory tasks; some children without impairment performed as poorly as the average child with language impairment. The authors concluded, “We found no evidence that auditory impairments are a necessary or sufficient cause of language impairments” (p. 1295). Likewise, the overlap between groups with and without dyslexia reported here and in numerous previous studies would show that impaired speech perception is neither a necessary nor a sufficient cause of dyslexia.

Although the general form of the argument offered by Bishop, Carlton, et al. (1999) is logically correct, it has a flaw. Its apparent force rests on the assumption that a single underlying determinant causes the disorder under consideration. If multiple factors contribute to that disorder, the argument loses power. Consider, for example, the relationship between cigarette smoking and lung cancer. Some smokers never get lung cancer, and some patients with lung cancer have never smoked. Nonetheless, it is well established that smoking sharply raises the probability of developing lung cancer.

Bishop, Bishop, et al. (1999) addressed the problem of contributory variables in specific language impairment, using Holmbeck’s (1997) general discussion of moderating etiological factors. Because reading is a complex skill, disorders of reading could arise from different configurations of disabilities, including impairments in speech perception. A factor that is neither necessary nor sufficient for dyslexia could still contribute to that condition. Given the variability in studies on dyslexia reported to date, future work should use large samples and employ numerous measures on each participant, including tests of both verbal and nonverbal abilities. Epidemiological analyses and other multivariate statistical methods such as inverse factor analysis could be used to evaluate whether different cases of developmental dyslexia are due to a contribution of factors or arise from a single basic disability.

Phonological and Word Position Effects in Sine-Wave Speech

Phonological Contrasts

Listeners with and without dyslexia found sine-wave words lacking both stops and fricatives easier to repeat than words containing stops or words containing fricatives. This difference reflects the absence of all the aspiration and friction noises that provide cues to stops and fricatives in natural speech. There was no interaction between phonological set and group. Listeners with dyslexia simply reported fewer words in any set than did participants without dyslexia.

In sine-wave utterances, the fourth sinusoid provides an explicit cue to the center frequencies of fricative resonances. Nevertheless, words with fricatives and no stops were not generally easier for all participants than words with stops and no fricatives. Brady et al. (1987) reported different findings on children who read poorly. When a masking noise was present, those children, compared to normal readers, missed isolated words with stops relatively more often than they missed words with fricatives. The data of Brady et al. and those of our study depart from the results of Cornelissen et al. (1996). Adults with dyslexia in the latter experiment had the most difficulty in identifying isolated CV syllables in noise when the consonant was a fricative. The broadband noise used by Cornelissen et al. may have masked cues to fricatives more effectively than the amplitude-match noise (see Schroeder, 1968) used by Brady et al.

Words with nasals were harder for listeners with and without dyslexia to comprehend than were words without nasals. Nasals produce transient antiresonances around the first three formants of natural speech, changing the short-term spectrum. The severely restricted spectral content of sine-wave speech would obscure this acoustic signature of nasals, yielding a significant nasal/non-nasal contrast. Again, no interaction occurred between phonological set and reading status.
Word Position

Listeners with and without dyslexia found words in the second position easier to report than words in the fifth position of seven-word utterances. The latter group showed this effect on the second and succeeding trials; the former showed it only on the last two trials. The participants without dyslexia reported words in the last position more readily than words in the fifth position on the final two trials. The performance of those with dyslexia never gave this result. (Those effects were apparently not large enough to produce a significant Position × Group interaction in the relevant ANOVA.) Our findings on differential effects of word position resemble the primacy and recency effects observed in memory for a list of unrelated auditory words. The earliest and the latest items in the list are recalled more accurately than are those in the middle.

The recency effect has been attributed to a short-lasting memory system, and the primacy effect is attributed to a longer-term system (see Baddeley, 1997). One possible interpretation of our results is that adults with dyslexia have a relatively ineffective short-lasting memory store. This prevents the appearance of a recency effect for sine-wave utterances. It also slows the appearance of a primacy effect, because this requires transfer of material from the short-lasting store to a longer-lasting one. In studies on memory that use a sufficiently long list of unrelated items, however, both recency and primacy appear on a single trial. In contrast, our participants without dyslexia required two trials on a seven-word sine-wave utterance before showing a primacy-like effect and three trials before showing a recency-like effect. These facts suggest that the two effects emerge as a consequence of developing an understanding of a sine-wave utterance over successive trials. The failure of listeners with dyslexia to manifest a recency-like effect would then be attributed to slower comprehension of a sine-wave utterance rather than to an inefficient short-lasting memory system. Of course, both factors could be at work.

In summary, adults with developmental dyslexia as a group perceived sine-wave speech less accurately than a group of control listeners. In general, group showed no significant interactions in various ANOVAs. The effect sizes for group differences were consistent, but not very large, again indicating overlap in performance by members of the two groups.

Digit Span and Sine-Wave Speech Comprehension

A shortened digit span is characteristic of many adults with dyslexia. Pauluisu et al. (2001) recently demonstrated this in participants from France, Italy, and the United Kingdom. In keeping with the general finding, our participants with dyslexia had a shorter digit span than the control participants. After reviewing numerous studies on children, Gathercole and Baddeley (1993, pp. 167–174) proposed that a reduction in the capacity of phonological memory contributes to developmental dyslexia, independently of lowered phonological awareness. If this remains true in adulthood, sine-wave utterances might present various degrees of memory load and hence various degrees of increased difficulty for listeners with dyslexia. This possibility already arose in our discussion of the effects of word position. As further evidence of it, a correlation should appear between digit span and performance on sine-wave speech by participants with dyslexia. Listeners without dyslexia should produce no such correlation, if the speech perception task presented most of them with a manageable memory load.

For the participants with dyslexia, digit span did correlate significantly with $P(C)$ combined over all sine-wave utterances. It also correlated with $P(C)$ on a substantial majority of 32 combinations of utterance and trial. The participants without dyslexia, in contrast, showed none of these effects. A test of nonverbal skill, Block Design, did not correlate with performance on sine-wave speech by either group. A reduced capacity in phonological memory apparently affects sine-wave speech comprehension by adults with dyslexia. This fits with the fact that our listeners with dyslexia, unlike those without dyslexia, did not show a significant recency effect with seven-word utterances.

A similar pattern of correlations appeared in a recent experiment on auditory frequency discrimination in adults with developmental dyslexia (France et al., 2002). Digit span correlated significantly ($p < .025$) and negatively with thresholds for those listeners in two of the eight different discrimination conditions; the correlations for three other conditions were marginal (.025 < $p$ ≤ .05). Listeners without dyslexia, however, did not even produce marginally significant correlation between digit span and frequency discrimination thresholds. Block design did not correlate with thresholds in either group.

The frequency discrimination task required transient retention of nonverbal auditory material in memory. The parallels between our present findings and those of France et al. (2002) suggest that individual adults with dyslexia might show a reduced immediate memory capacity for any sort of auditory material, verbal or nonverbal. The shorter digit span characteristic of dyslexia would be one facet of a general impoverishment of the capacity of auditory memory. In turn, such a deficit could contribute to the adult dyslexic’s disabilities in various auditory tasks (see Wright, Bowen, & Zecker, 2000, for a review), including speech perception.
Acknowledgment

This research was supported by the Rodin Remediation Trust and by the Wellesley Trust. We thank Jonathan Winter for technical support and the late Nancy C. Waugh for numerous helpful comments on drafts of this article.

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Received March 12, 2002
Accepted July 31, 2002
DOI: 10.1044/1092-4388(2003/006)
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