Auditory Temporal Processing and Lexical/Nonlexical Reading in Developmental Dyslexics

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Abstract

Relationships between lexical/nonlexical reading and auditory temporal processing were examined. Poor nonlexical readers (poor nonword readers, phonologic dyslexics) had difficulty across tone tasks irrespective of speed of presentation or mode of recall. Poor lexical readers (poor irregular word readers, surface dyslexics) had difficulty recalling tones in a sequence only when they were presented rapidly. Covariate analysis supported these findings, revealing that nonlexical (nonword) reading performance is associated with general auditory performance, but lexical (irregular word) reading is particularly associated with auditory sequencing. These findings suggest that phonologic and surface dyslexics perform differently on nonspeech auditory tasks. Because the two different types of poor readers did not differ significantly on tests of memory and learning but did differ on auditory tasks, we suggest that their performance on the auditory tasks may reflect auditory processing abnormalities as opposed to more general learning or memory difficulties. In addition to these observed qualitative differences between groups on the tone tasks, collapsing groups (all readers) revealed significant correlations between nonword reading and the Same-Different tone tasks in particular, whereas irregular word reading was not associated with any tone tasks; there also appears to be a quantitative relationship between nonlexical reading and Same-Different tone task performance as better or worse nonword reading predicts better or worse performance on the Same-Different tone tasks. In particular, it is conceivable that an auditory temporal processing deficit might contribute to poor nonword reading.

Key Words: Auditory processing, dyslexia, reading, temporal sequencing

Abbreviations: c-v = consonant-vowel, g-p = grapheme to phoneme, ISI = interstimulus interval, MMF = magnetic mismatch field, TOMAL = Test of Memory and Learning

Some investigators have suggested that poor reading results from an auditory temporal processing impairment, making it difficult for children to hear acoustic changes in speech sounds (Tallal, 1980; De Weerd, 1988; Reed, 1989; Watson and Watson, 1993; Wright et al, 1997; see also Tallal et al, 1985; Watson and Miller, 1993). Not hearing such changes could lead to poor speech perception and hence poor learning of the grapheme-phoneme (g-p) relationships required in nonword reading. Authors of this opinion propose that poor readers' difficulty in detecting, distinguishing, or hearing rapidly presented successive tones taps into these speech perception problems. The presumption is founded on the idea that particular tone presentation properties reflect speech properties. Transitions from a stop consonant to a vowel (c-v), for example, are within the 10- to 50-msec range. If a child cannot detect or discriminate the order of two tones presented at rates at least as fast as 20 msec and has difficulty on c-v discrimination or sequencing tasks, some authors would view this parallel as a causal one.

Although the claim that poor auditory temporal processing skills are related to poor reading performance is gaining support, the nature of the associated linguistic variables is not clearly understood. Are both lexical and nonlexical reading associated with auditory temporal processing or just nonlexical reading? What are the
relationships among auditory skills, speech perception, and reading? Prior studies have typically used nonword reading measures to determine reading skills; hence, findings suggested that nonlexical reading was related to poor auditory temporal processing. However, lexical reading has yet to be examined for a possible relationship with this type of processing.

**Behavioral Evidence For and Against Auditory Temporal Processing Deficits in Poor Readers**

If poor reading is linked to an auditory temporal processing deficit then it might be difficult for children to hear those acoustic changes in speech sounds underlying appropriate g-p correspondences (Tallal, 1980; De Weerd, 1988; De Marco et al., 1989; Reed, 1989; Watson and Watson, 1993; Wright et al., 1997). As early as 1975, Tallal and Piercy showed that the poor performance of dysphasics on stop c-v syllables was due to an impaired ability to process a transitional component of auditory information or to the short duration of the stimulus presentation. Speech stimuli were modified via a computer to change the temporal components so that vowel-vowel syllables had steady-state brief 50-msec durations and c-v formant transitions were extended. Tallal and Piercy found that the performance of dysphasics on stop c-v syllables was impaired on steady-state vowel sounds of brief durations and that their performance was improved when c-v formant transitions were extended. They concluded that an auditory temporal processing deficit disrupted the ability of dysphasics to detect the short-duration acoustic information essential for normal speech perception.

Later, Reed (1989) presented poor readers (ages 7.9–10.4) with synthesized c-v syllables (ba/da) and found that if the children could not process the order in which they heard the sounds, they could not discriminate between the sounds (or vice versa). Reed also presented two 75-msec tones (same design as Tallal, 1980), in addition to the speech sounds, at interstimulus intervals (ISIs) of 10 to 400 msec and found that the temporal order judgments of poor readers were significantly impaired relative to controls as ISIs decreased for both tone and c-v pairs. As Tallal would have predicted, the poor readers did not have difficulty mimicking vowel pairs. Thus, poor c-v performance could be a result of difficulty in detecting the c-v transition.

Very recently, however, Mody et al. (1997) selected good and poor readers who differed on temporal order judgment of /ba/ /da/. When given the more easily discriminated pairs of /ba/ /sa/ and /ba/ /ta/, the groups no longer differed. In addition, groups did not differ on discriminating nonspeech sine wave analogs of the second and third formants of /ba/ /da/, nor did they differ on sensitivity to brief transitional cues varying along a synthetic speech continuum. These authors concluded that the poor readers had a speech-specific, as opposed to an auditory, deficit. But, since poor readers were selected based on an inability to sequence /ba/ /da/, they may not have had a temporal processing disorder for speech tasks in general but perhaps just this task.

Evidence against Mody et al.'s (1997) theory may now exist. Diesch and Luce (1997) examined magnetic mismatch fields (MMFs) of the pairs /da/ /ga/ and then /da/ /ba/, which were presented to neurologically and audiologically normal subjects. The MMFs for /da/ /ba/ were in a different location (more anterior) than the MMFs for /da/ /ga/. As these speech sound pairs may be processed differently, it is certainly possible that dyslexics could have difficulty mimicking the temporal order of /ba/ /da/ but not /da/ /ga/ if damage to cells/systems/locations responsible for /ba/ /da/ perception specifically is deficient.

Given different views as to whether causal relationships exist among auditory, speech, and reading processes, Tallal’s (1980) study, the most recognized study of auditory temporal processing skills in dyslexics, is herein addressed. Tallal tested poor readers for rapid auditory temporal processing difficulties and demonstrated that, compared to controls, dyslexics had difficulty discriminating and sequencing two tones when they were presented rapidly (8- to 305-msec ISIs) as opposed to slowly (428-msec ISI). Poor readers with both poor oral language and nonword reading scores showed a significant correlation between their nonword reading and rapid sequencing scores (r = .81). Poor readers without poor oral language did not show this correlation. The present study duplicates Tallal’s (1980) study and, in addition, addresses the issue of heterogeneity of dyslexic subtypes via the use of lexical versus nonlexical reading measures.

In addition to heterogeneity issues that have yet to be addressed in the auditory temporal auditory processing literature, questions regarding the nature and definition of auditory temporal processing abnormalities will be addressed. Are tone properties and/or speech stimuli properties or more general linguistic or memory factors responsible for poor performance on these
tasks? Are lexical and nonlexical reading associated with rapid or slow auditory presentations, with temporal order (sequencing) or confounds within Same-Different performance? These issues have been addressed in the present study to determine what tone, speech, or memory variables are associated with lexical and nonlexical reading.

Tallal's repetition subtests vary Sequencing and Same-Different, as well as fast (8- to 305-msec) and slow (428-msec) ISI presentations, to examine temporal ordering and rapid temporal processing skills, respectively. As such, groups can differ on tasks requiring (Sequencing) or not requiring (Same-Different) knowledge of temporal order, as well as on tasks requiring the perception of slow (428-msec) or rapid (8- to 305-msec) tone presentations. These tests, along with irregular words (lexical) and nonwords (nonlexical), were used in covariate/partial correlation analyses to examine relationships with Sequencing, Same-Different, and rapid and/or slow processing to determine whether temporal processing components underlie different reading patterns. Possible effects of general memory or learning performance on group differences are determined by using subtests of the Test of Memory and Learning (TOMAL) in covariate analyses.

Group comparisons in this study include good versus poor and lexical versus nonlexical reading performance. However, phonologic versus surface dyslexic reader groups are also used periodically when further support for findings is sought.

METHOD

Subjects

Of the 89 children from primary schools throughout Sydney, Australia, who participated, 44 were poor and 45 were good readers. Seventy of these children (34 poor and 36 good) completed the Repetition Test and the remaining 19 children were included for their data on any or all of the following: TOMAL (Reynolds and Bigler, 1994) and Castles Word/Nonword Test (Coltheart and Leahy, 1996). These same subjects were administered the Ternus test of visual motion detection; results of the Ternus analysis are outlined in Cestnick and Coltheart (1998).

Most poor readers (37) were from the Multilit Reading Program, Macquarie University (an intensive three-term reading remediation program). Others (8) were obtained from primary school reading programs in Sydney, Australia. Good readers were obtained via an advertisement placed in a Sydney newspaper requesting participation in a study on reading and learning in exchange for psychometric/language reports. Parent, teacher, and audiologist (when relevant) interviews revealed no obvious hearing deficits in the children, with the exception of one good and one poor reader who both had slight hearing impairments in the high-frequency range. The Castles Word/Nonword Test (Coltheart and Leahy, 1996) determined the reading levels. Reading skill levels of the select few children who did not complete the Castles Word/Nonword Test were obtained by specialists in their reading remediation program or teacher reports. These select cases were not used in any analyses examining nonword or irregular word reading but were used in basic good versus poor reader comparisons on tone tasks.

Periodically, in addition to the use of good and poor reader groups, or all children as a whole (when examining lexical versus nonlexical reading), poor readers are divided into phonologic and surface dyslexic groups for supporting or further analyses. These dyslexic subtypes were determined by calculating the difference between lexical and nonlexical reading scores. The distribution of these difference scores in the good reader group was used to construct a 95 percent confidence interval. Surface dyslexia was then defined by a negative difference score outside the confidence interval for good readers. Phonologic dyslexia was defined by a positive difference score outside the good reader confidence interval. It should be noted that despite the different lexical versus nonlexical reading patterns of the poor readers, both the lexical and nonlexical scores of most were below the all-reader median. Thus, it was neither both poor irregular and nonword reading nor the poor reading of one of these word types in isolation that contributed to differences between these groups but the strength of using one reading route over the other.

Test Procedures

Repetition Test

The Repetition Test, devised by Tallal (1980), was used to examine auditory temporal processing skills. Participants listened to two complex tones. The fundamental frequency of one tone was 100 Hz, the other 305 Hz. The duration of each tone was 75 msec. The tones were presented binaurally via earphones at a sound
pressure level of 70 dB. The child moved a lever left or right either to discriminate between the tones or to identify orders of presentation of the tones. The time interval between tones was varied in order to detect possible auditory temporal processing difficulties. In the present study, the goal was to determine whether poor performance on such a task is unique to phonologic dyslexics, as opposed to surface dyslexics, or common to all poor readers.

The Repetition Test consists of five subtests: Association, Sequencing, Rapid Perception, and two Same-Different tasks (slow and fast). The Rapid Perception subtest is the Sequencing subtest with shorter ISIs. We refer to it here as Fast Sequencing.

**Association Subtest**

Adequate performance on this subtest was essential to performance on the other tasks. In the Association subtest, children were trained to respond to each tone by moving a lever to the left or right to denote the low- or high-pitched tone, respectively. Training continued until a criterion of at least 20 of 24 correct consecutive responses was reached. Most subjects reached criterion during only one trial of 24; however, a few required a second run through the subtest to reach 20 of 24. No children required more than two runs through the program, and there was no difference between good and poor readers on the mastering of this task. Mean raw scores were not significantly different.

**Slow Sequencing Subtest**

Once Association between the tones and responses required was demonstrated, the Slow Sequencing subtest was performed. Children were trained to respond to the two tones presented in succession, separated by a 428-msec ISI for the four possible two-tone patterns (1-1, 2-2, 1-2, 2-1) by moving the lever left or right in the order of presentation (left = low/1 tone; right = high/2 tone). Following the 8 training trials with knowledge of results, 24 trials without knowledge of results were given.

**Fast Sequencing Subtest**

In this test, the same series of 24 two-tone patterns used in the Slow Sequencing subtest were used again; however, instead, the ISI, previously held constant at 428 msec, was now systematically decreased. Six ISIs are included in this subtest: 8, 15, 30, 60, 150, and 305 msec. Each child received a total of 24 two-tone patterns, 4 at each of these ISIs. Comparisons between the Slow and Fast Sequencing subtests, which differ only in stimulus offset-onset times (ISI), identify a temporal processing deficit. If the Fast Sequencing scores are significantly lower than the Slow Sequencing scores, a temporal processing deficit is assumed.

**Slow Same-Different Subtest**

The lever was turned 90 degrees to avoid confusion on this test. Now, children moved a lever up/down (as opposed to left/right) for same/different choices respectively. Children were initially presented with two identical tones separated by a 428-msec ISI and trained to move the lever up to indicate that they were the same. The procedure was discontinued after 10 consecutively correct responses. They were then presented with two different tones separated by a 428-msec ISI and trained to press the bottom button to indicate that they were different; discontinuation was after 10 consecutively correct responses. Next, children were presented with either two identical or two different tones and were required to move the lever up or down for same or different; this continued until 20 of 24 were correct. If, after 48 trials, a child did not meet criterion, the test was discontinued. All children met the criterion.

**Fast Same-Different Subtest**

The same 24 two-tone patterns from the Slow Same-Different task were used but now the ISI was varied from 8 to 305 msec, as was the case in the Fast Sequencing subtest. As in the Slow Same-Different task, children were required only to indicate whether the two tones in each sequence were the same as or different from each other.

Comparisons between the Slow and Fast Same-Different subtests reflect the effect of ISI on Same-Different tasks, and comparisons between Slow-Sequencing/Slow Same-Different and Fast-Sequencing/Fast Same-Different reflect temporal order recall.

**TOMAL (Test of Memory and Learning)**

Six subtests of the TOMAL were administered: (1) Word Selective Reminding (a free recall auditory test [recalling word lists] with corrective feedback), (2) Digitspan (serial free recall test), (3) Letterspan (serial free recall test), (4) Abstract Visual Memory (subjects recall
abstract visual shapes in any order; view a shape, and find it among several similar shapes),
(5) Visual Sequential Memory (subjects look at
many abstract shapes; the page is turned, and
subjects point to the order in which they saw the
shapes), and (6) Motor Imitation (instructor's hand movements are repeated). These subtests
can be examined in isolation or auditory versus
visual or sequential versus nonsequential cate-
gories to make comparisons across reading
groups.

Castles Word/Nonword Test

Thirty regular, 30 irregular, and 30 non-
words were presented randomly to children via
flashcards (one word per card) and scored accord-
ing to number correct out of 30 for each word
type. Norms for this test came from Coltheart

RESULTS

Sequencing versus Same-Different
Task Performance

If it is the case that poor readers have diffi-
culty mimicking the temporal order of auditory
stimuli, they should be significantly worse at
Sequencing as opposed to Same-Different tasks,
and if they have difficulty with rapid temporal per-
ception, they should also be significantly worse
at rapid versus slow presentations, compared to
good readers. If poor rapid temporal processing
underlies poor speech perception and hence poor
g-p learning required in nonword reading, one
might hypothesize that perhaps temporal (Sequencing) and/or rapid (8- to 305-msec) pro-
cessing will be related to nonword reading, as
opposed to irregular word reading. We first con-
sider differences on Sequencing and Same-
Different performance.

Good versus Poor Readers

Do good and poor readers actually differ on
specific subtests of Tallal's Repetition Test? If so,
do irregular or nonword reading differences
between these groups contribute to group dif-
fences? First, we compare good and poor read-
ers on each of these auditory subtests. Figure 1
shows mean raw scores for all subtests. Note that
the test ceiling is a raw score of 24. Table 1
summarizes means and standard deviations for
each subtest for each reader group. Good and
poor readers differed significantly on four of the
five subtests of the Repetition Test. All readers
reached criterion on the Association subtest, and
these mean scores did not differ signifi-
cantly. On each of the other four subtests, how-
ever, the mean difference between good and
poor readers was significant. The results of Stu-
dent's t-test for 68 degrees of freedom were as
follows: Slow Sequencing, p = .001; Fast Sequenc-
ing, p = < .001; Slow Same-Different, p = .002;
and Fast Same-Different, p < .001.

These findings replicate those of Tallal
(1980), with the exception of the significant dif-
fferences found between good and poor readers
on the slower (428-msec ISI) Sequencing and
Same-Different subtests. Note, however, that
Tallal's groups would have been more reading or
IQ age matched (most of control group 0-6 years
old, half of poor reader group 7-12 years) and
ours more chronologically age matched (7-12),
leaving open the possibility that our differences
reflect general natural improvement and devel-
opment in good but not poor readers on the
Sequencing/Same-Different task performance.

Figure 1 Mean raw scores for good and poor readers
on five subtests of the Repetition Test. Horizontal line at
24 indicates maximum possible score (test ceiling). Assoc
= Association Subtest, Slow Seq = Slow Sequencing Sub-
test, Fast Seq = Fast Sequencing Subtest, Slow SD = Slow
Same-Different Subtest, Fast SD = Fast Same-Different
Subtest.

Table 2 shows the percentage of children who had
perfect scores on the Sequencing and Same-
Different subtests. Many good readers scored
perfectly on Slow Sequencing (69.4%), whereas
fewer poor readers did (23.5%) (see Table 1).
Yet Tallal (1980) failed to find a significant dif-
fERENCE between reader groups. Performance on
our Slow Same-Different test was slightly higher,
revealing 86 percent of good and 64 percent of
Table 1 Mean Raw Scores and Their Standard Deviations on All Repetition Test Subtests for Good and Poor Readers

<table>
<thead>
<tr>
<th>Subtest</th>
<th>N</th>
<th>Assoc</th>
<th>Slow Seq</th>
<th>Fast Seq</th>
<th>Slow SD</th>
<th>Fast SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Good readers</td>
<td>36</td>
<td>23.03</td>
<td>3.20</td>
<td>23.19</td>
<td>1.62</td>
<td>23.47</td>
</tr>
<tr>
<td>Poor readers</td>
<td>34</td>
<td>21.65</td>
<td>5.62</td>
<td>20.74</td>
<td>3.99</td>
<td>20.62</td>
</tr>
</tbody>
</table>

Assoc = Association, Slow Seq = Slow Sequencing, Fast Seq = Fast Sequencing, Slow SD = Slow Same-Different, Fast SD = Fast Same-Different.

poor readers with perfect scores. The significant mean raw score difference between the groups was largely attributed to a few poor readers (14.7%), as 85.3 percent of poor readers were at or above the good reader floor (15/24). Tallal stated that in her Slow Same-Different condition, as in her Slow Sequencing condition, most children demonstrated errorless or high performance, and the differences between good and poor readers were not significant.

Because good and poor readers can differ in either irregular (lexical) and/or nonword (nonlexical) reading performance and these word types are correlated with each other, it is necessary to remove the effects that irregular and nonword reading have on each other to determine whether differences in irregular or nonword reading are contributing to group differences on the Repetition subtests. To examine lexical versus nonlexical routes respectively, analyses of covariance (ANCOVA) were run using the individual Repetition subtest scores of good and poor readers with irregular and then nonwords treated as covariates.

Because children whose speech perception is poor before learning to read will have particular difficulty learning g-p rules and nonwords are read via application of g-p correspondences, we hypothesized that only differences in nonword reading would contribute to the Repetition subtest differences (when irregular words were the covariate). Stated differently, as irregular words are read via an orthographic whole-word sight recognition process or at least are not read via g-p correspondences, this reading would not be associated with auditory perception, and hence group differences on irregular word reading should not contribute to differences on the Repetition subtests (when nonwords were the covariate).

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More specifically, analyses of nonword reading of these groups with irregular words as covariates should show significant group effects; however, irregular word reading of these groups with nonword reading as a covariate should not show the group effect, if it is true that nonword reading is affected by auditory perception and irregular word reading is not.

Irregular/Nonword Effects on Good versus Poor Reader Differences

Fast Same-Different Subtest

Fast Same-Different results by group with nonword reading as a covariate were not significant [F (1, 62) = 0.64, p = .425] but with irregular word reading as a covariate were significant [F (1, 62) = 8.04, p = .006]; the group differences on the Fast Same-Different task were associated with differences in nonword reading only and irregular word reading was not associated with this task. This fits the hypothesis that only nonword reading should be associated with auditory tasks thought to mimic speech perception qualities relevant to nonword reading. Interestingly, although this Fast Same-Different analysis reveals the predicted pattern of auditory performance effects on nonword as opposed to irregular word reading, the other auditory tasks did not demonstrate this predicted relationship.

Slow Same-Different Subtest

Although Slow Same-Different results by group with nonword reading as the covariate
were not significant \( F(1, 62) = 0.17, p = .678 \), neither were they with irregular word reading as the covariate \( F(1, 62) = 0.56, p = .459 \); a shared relationship between irregular and nonword reading, outside of lexical versus nonlexical processes, contributes to the differences found between reader groups. This analysis clarifies that nonword/nonlexical reading is uniquely associated with Fast Same-Different as opposed to Slow Same-Different performance.

**Fast Sequencing Subtest**

Fast sequencing by group with irregular word reading as the covariate was significant \( F(1, 62) = 8.97, p = .004 \); however, this was also the case with nonword reading as the covariate \( F(1, 62) = 7.63, p = .008 \). Both lexical and nonlexical reading are associated with differences in Fast Sequencing performance. Contrary to our expectation, this only partially fits the hypothesis since irregular word reading is also associated with this auditory task.

**Slow Sequencing Subtest**

Slow Sequencing with irregular word reading as the covariate was also significant \( F(1, 62) = 9.12, p = .004 \); however, it was also significant with nonword reading as the covariate \( F(1, 62) = 8.69, p = .005 \). Both nonword and irregular word reading are involved with Slow Sequencing and, of course, both sequencing tasks. Again, the relationship with irregular word reading was not expected.

**Association Subtest**

Association by group with irregular word reading as the covariate was not significant \( F(1, 62) = 0.38, p = .544 \), nor was it with nonword reading as the covariate \( F(1, 62) = 1.67, p = .202 \). Reading is not significantly related to this task, as expected: it is a control condition to ensure that readers can do the task and that the groups did not differ on earlier tests.

**Memory Covariates**

Because good and poor readers also differed on all TOMAL subtests, it might be the case that their differences on Tallal's Repetition subtests could result from differences in more general confounds of memory/learning (or problem solving). As such, ANCOVA analyses were also run using all TOMAL subtests as simultaneous, and then individual covariates for each of the good and poor reader comparisons on the Repetition tone tests. These analyses revealed that memory/learning did not play a role in group differences on any of the subtests, with the exception of the Slow Same-Different task. Using TOMAL subtests simultaneously or individually as covariates in the group analyses did not alter or render any significance levels insignificant, with the exception of the Slow Same-Different task, where simultaneous and individually tested covariates rendered the difference between good and poor readers as insignificant (all covariates \( 54, 1 \) 0.37, \( p = .545 \); letterspan \( 61, 1 \) 0.00, \( p = .95 \); digitspan \( 61, 1 \) 0.59, \( p = .445 \); motor sequencing \( 61, 1 \) 0.61, \( p = .436 \); visual sequencing \( 61, 1 \) 2.54, \( p = .116 \); wsr \( 62, 1 \) 1.06, \( p = .308 \); note that abstract memory remained significant \( 62, 1 \) = 6.06, \( p = .017 \). This also supports the possibility that Tallal’s lack of group differences on this subtest may have been a result of the fact that her groups were matched for learning/memory skills (normally developing younger children were matched with delayed older children in good and poor reader groups, respectively).

An alternative explanation for our finding of an association of the Slow Same-Different task with learning and memory is the fact that the response box was turned, during this task, so that the response choice was now up and down (for same and different choices) as opposed to left to right (for high and low tone choices in the Sequencing tasks). This was done in order to avoid confusion in task requirement. Given this likelihood, the data also support the conclusion that group differences on the other four-tone tasks could not be attributed to differences in mastery of the task.

**Summary**

In summary, the differences between good and poor readers on sequencing and rapid auditory perception tests are related to their different reading patterns (lexical/nonlexical), but Slow Same-Different performance is related to differences in memory/learning performance.

As predicted, it was the case that Fast Same-Different auditory performance was associated with nonword reading only (as well as letterspan); however, it was not the case that performance on Sequencing tasks was only associated with nonword reading, since irregular word reading was also related to Sequencing. Given these findings, the hypothesis that
only nonlexical reading would have a relationship with auditory perception does not necessarily hold.

The present results establish that there is a relationship between nonlexical reading and the Fast Same-Different auditory task, as well as between nonlexical and lexical reading and the Sequencing tasks (both slow and fast). Using good and poor readers in this analysis suggests that poor versus good nonlexical/lexical reading leads to differences on these tests. To confirm this hypothesis, we now consider dyslectic subtypes.

Surface and Phonologic Dyslexics

Some poor readers are good at reading via one route relative to the other. Phonologic dyslexics are better at lexical reading, whereas surface dyslexics are better at nonlexical reading. If both irregular and nonword reading contribute to Sequencing differences and nonword reading differences contribute to Fast Same-Different differences, surface dyslexics with poor irregular word reading should perform poorly on Sequencing, and phonologic dyslexics with poor nonword reading should perform poorly on both Fast Sequencing and Fast Same-Different tasks compared to good readers.

Table 3 compares mean raw scores on all subtests for good readers, phonologic dyslexics, and surface dyslexics. Figure 2 shows these same data graphically. When good readers were compared to surface and phonologic dyslexics on the Repetition subtests, the findings precisely supported the above ANCOVA analysis. Surface dyslexics (n = 3) were significantly worse than good readers on Fast Sequencing \([t(13.68) = 4.18, p = .001; \text{unequal variance assumed}]\) but not on Fast Same-Different (in fact, all surface dyslexics scored perfectly on both Same-Different tasks). In fact, when the diagnostic criterion was relaxed slightly to include poor readers at or slightly within good reader irregular nonword word reading difference intervals (n = 6; n = 9), most scored perfectly (4/6, 7/9). In addition, phonologic dyslexics (n = 7) differed from good readers on both Fast Sequencing \([t(41) = 2.53, p = .015]\) and Fast Same-Different \([t(41) = 4.18, p < .001]\), similar to the results of earlier ANCOVAs demonstrating nonword reading associations with these tasks; they also differed from good readers on the Slow Same-Different task \([t(41) = 3.38, p = .002]\).

Phonologic and surface dyslexics themselves (with good irregular vs nonword reading respectively) should differ on the Fast Same-Different test if, as earlier analysis demonstrated, irregular word reading does not lead to differences in this test performance but nonword reading does. This, in fact, was the case; phonologic and surface dyslexics differed only on the Fast Same-Different subtest \([t(6) = 2.701, p = .036]\). Phonologic dyslexics had significantly lower scores than surface dyslexics (Slow Same-

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Mean Raw Scores and Their Standard Deviations on All Repetition Test Subtests for Good Readers, Phonologic Dyslexics, and Surface Dyslexics</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Assoc</td>
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<tr>
<td></td>
<td>Mean</td>
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<td>Good readers</td>
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<td>Phonologic dyslexics</td>
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<tr>
<td>Surface dyslexics</td>
<td>03</td>
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</tbody>
</table>

Assoc = Association, Slow Seq = Slow Sequencing, Fast Seq = Fast Sequencing, Slow SD = Slow Same-Different, Fast SD = Fast Same-Different.
Different performance was almost significantly different between these groups \( t(8) = 2.27, p = .063 \) and may have been significantly different if more items had been presented to demonstrate precociousness of surface dyslexics on this task.

**All Readers**

Group comparisons are essential to examine qualitative differences in performance on both tone and reading tasks; however, collapsing groups also offers useful quantitative information regarding more general relationships between tone task and reading performance. As such, the groups were collapsed (all participants), and their nonword and irregular correlations with each of the tone tasks were examined. These analyses revealed two significant correlations between nonword reading and both Same-Different tasks only: Fast Same-Different, \( .42 \) \( (60) p = .001 \), and Slow Same-Different, \( .26 \) \( (60) p = .040 \). No significant correlations were observed between irregular word reading and any of the tone tasks when all subjects were used in the analyses. This demonstrates a more general quantitative relationship between nonlexical reading and Same-Different tone task performance as both nonword reading and the Same-Different tone task may share similar processes. Also, because irregular word reading and auditory Sequencing relationships exist given specific reader group comparisons but do not exist given correlational analyses with a more general population, they successfully isolate the good and poor reader groups. Further correlational analyses are outlined in another work (Cestnick and Jerger, 2000).

**Summary**

These analyses support the concept that nonlexical reading is associated with both Fast Same-Different and Fast Sequencing performance, and that lexical reading is associated with Sequencing performance only. This was evidenced by two different forms of analysis: (1) ANCOVAs, where poor nonword reading (and letterspan) only was associated with poor Fast Same-Different performance whereas both poor nonword and irregular word reading were associated with poor Sequencing performance, and (2) dyslexic subtypes, where surface dyslexics (with poor irregular relative to nonword reading) performed poorly on Fast Sequencing (Slow Sequencing scores were also low) but scored perfectly on Same-Different tasks whereas phonologic dyslexics (with poor nonword relative to irregular word reading) performed poorly on both the Fast Same-Different and the Sequencing tasks. Collapsing groups reveals a strong relationship between nonword reading and Same-Different tone tasks.

Stated differently, those who over-rely on the nonlexical route (surface dyslexics) have exceptional Fast Same-Different auditory performance. Those who over-rely on the lexical route (phonologic dyslexics) do not do as well on the Fast Same-Different task. Good readers, who are likely to rely on the lexical route but do not have a poor nonlexical route, do well on all auditory tasks in general.

So, lexical and nonlexical reading are differentially associated with the auditory tone tasks, but what properties of the tone tasks are associated with lexical and/or nonlexical reading? Tallal's Repetition subtests vary Sequencing and Same-Different, as well as fast and slow ISI presentations. In line with our hypothesis, if nonword reading requires detailed c-v speech perception skills, which, in turn, requires the ability to perceive rapid c-v formant transitions, then nonlexical reading should be associated with rapid processing and lexical reading should not.

**Rapid versus Slow Presentation**

In accordance with prior research suggesting that poor readers have had difficulty detecting or distinguishing rapidly presented successive stimuli (short ISIs) (McCroskey and Kidder 1980; Farmer and Klein 1993), poor readers in the present study should have significantly lower scores on fast versus slow tone presentations, irrespective of Sequencing or Same-Different task requirements, and good readers should not. Failing to show overall poor performance on short as opposed to long ISIs would suggest a different etiology behind poor performance (other than rapid and successive presentation) such as confounds of Sequencing or Same-Different task performance. In terms of heterogeneity and in accordance with our original hypothesis, nonlexical reading is more apt to be affected by temporal auditory processing difficulties than lexical reading if the difficulties affect speech (rapid formant transitions) perception necessary for g-p learning (nonlexical...
Irregular words would not be affected as this type of reading involves orthographic analysis as opposed to piecemeal g-p application affected by poor perception of subtle changes in speech.

**Fast (8–305 msec) versus Slow (428 msec) Sequencing**

When the duration of the interval between the two tones was decreased (305- to 8-msec ISIs) in the Fast Sequencing condition, a difference between good and poor readers was found, as expected. When Fast Sequencing scores were subtracted from Slow Sequencing scores and good and poor readers' difference scores compared, poor readers' (mean = 2.79, SD = 3.35) difference scores were significantly greater than good readers' (mean = 1.19, SD = 2.16), \[t (68) = -2.39, p = .0201.\] This demonstrates that poor readers were significantly worse at Fast versus Slow Sequencing than controls (poorer at short ISIs). Tallal (1980) did not find a difference between good and poor readers on Slow Sequencing but did on Fast Sequencing, yet our groups significantly differed on both subtests. These findings suggest a difference between our groups on these two tests as well, although our poor readers performed worse or good readers performed better on Slow Sequencing than Tallal's subjects. As demonstrated earlier, although our poor readers performed significantly lower than good readers on Fast Sequencing, this was largely attributed to a few poor readers (14.7%), as 85.3 percent of poor readers were at or above the good reader floor (15/24). Discounting one good reader with 15 of 24 on the Fast Sequencing subtests, 35 percent of poor readers would be under the next good reader floor (17/24). Forty-five percent of Tallal's (1980) poor readers were outside of the good reader floor.

**Irregular/Nonword Covariates**

Since good and poor readers differ on nonword and irregular word reading and differences between slow and fast processing could be due to these nonword reading differences (as predicted), the same group comparison was run using nonwords and then irregular words as covariates. When irregular word reading was the covariate, the groups no longer differed in their Slow-Fast Sequencing performance \[F (60, 1) = .00, p = .965,\] nor did they differ when nonword reading was the covariate \[F (60, 1) = .02, p = .887.\] A shared relationship between irregular and nonword reading contributed to the original differences in Slow-Fast Sequencing differences. We thought this interesting since earlier analysis had demonstrated that both nonwords and irregular words were also associated with Fast Sequencing performance.

So, poor readers perform significantly worse on fast relative to slow processing of brief tones in a Sequencing paradigm than good readers, and both irregular and nonword reading differences are collectively associated with these differences. The fact that differences in lexical/irregular word reading were associated with differences in tone presentation rates was surprising, and reasons for the relationship are uncertain. To examine the effect more closely, phonologic and surface dyslexic data are next examined.

**Phonologic versus Surface Dyslexics**

Given the prior demonstration that irregular word reading was associated with Fast Sequencing but nonwords were associated with both Fast Sequencing and Fast Same-Different performance, relationships between general rapid processing and lexical reading have been eliminated but have not been eliminated with non-lexical reading. Analogously, because surface dyslexics had significantly poor Fast Sequencing performance and phonologic dyslexics had significantly poor performance on this task and the Fast Same-Different task, the probability of a general rapid processing deficit in surface dyslexics has been eliminated (or they would not have scored perfectly on the Fast Same-Different task) but has not been eliminated in phonologic dyslexics who did poorly at both Fast Sequencing and Same-Different tasks. So, poor lexical reading (in relation to nonlexical reading; surface dyslexics) does not dictate poor general rapid temporal processing performance; however, poor nonlexical reading does.

**Fast (8–305 msec) versus Slow (428 msec) Same-Different**

Like Tallal (1980), results of our Same-Different subtests mirrored those found on our Sequencing subtests. The faster Same-Different task produced significantly lower scores than the slower one. Table 4 shows the percentage of children yielding perfect scores for Sequencing and Same-Different subtests. The Same-Different tasks were easier for most
Table 4  Percentage of Subjects Yielding a Perfect Score for Sequencing and Same-Different Subtests

<table>
<thead>
<tr>
<th></th>
<th>Sequencing</th>
<th>Same-Different</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slow (428 msec)</td>
<td>Fast (8–305 msec)</td>
<td>Slow (428 msec)</td>
<td>Fast (8–305 msec)</td>
</tr>
<tr>
<td>Good readers</td>
<td>69.4</td>
<td>41.7</td>
<td>86.0</td>
<td>70.1</td>
</tr>
<tr>
<td>Poor readers</td>
<td>23.5</td>
<td>5.9</td>
<td>64.0</td>
<td>38.2</td>
</tr>
<tr>
<td>Phonologic dyslexics</td>
<td>57.1</td>
<td>14.3</td>
<td>42.9</td>
<td>42.9</td>
</tr>
<tr>
<td>Pure surface dyslexics</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

subjects than the Sequencing tasks, with more perfect scores on these Same-Different tasks.

When Fast Same-Different scores were subtracted from Slow Same-Different scores and mean difference scores compared, poor readers’ difference scores were significantly higher (mean = -2.50, SD = 3.11) than good readers’ (mean = 0.33, SD = 1.17), [t (68) = -3.90, p < .001].

**Irregular/Nonword Covariates**

If deficiencies in temporal processing lead to poor speech perception and hence poor reading, then the difference between good and poor readers on the Slow and Fast Same-Different scores is more likely to be at least partially due to their differences in nonword reading as opposed to irregular word reading. As such, nonword/irregular word reading scores were treated as covariates in this group comparison as well, and this was precisely what was found. When the groups were compared and irregular word reading effects were removed, thereby leaving nonword reading differences, the groups differed significantly [F (60, 1) = 8.12, p = .006]. However, when nonwords were the covariate, thereby examining irregular word differences, the groups did not differ [F (60, 1) = 1.26, p = .266].

**Phonologic versus Surface Dyslexics**

If nonlexical/nonword reading differences are associated with temporal processing differences but lexical/irregular words are not, we should also see that phonologic dyslexics with poor nonword reading significantly differ from good readers, but that surface dyslexics with good nonword reading (relative to irregular word reading) do not. This was the case. The Slow-Fast Same-Different scores of good readers and phonologic dyslexics differed significantly [t (41) = -2.51, p = .016], whereas the difference scores of good readers and surface dyslexics were not significantly different. So, poor nonlexical reading is associated with poor rapid auditory processing but poor irregular word reading is not. This agrees with our prediction that phonologic dyslexics should show significant differences between fast and slow but surface dyslexics should not. It is interesting to note that none of the surface dyslexics scored perfectly on either Sequencing test, but they all scored perfectly on both Same-Different tests. So, where phonologic dyslexics appear to have differences in Fast versus Slow Sequencing, surface dyslexics appear to have differences between Sequencing and Same-Different performance.

Why both irregular and nonword differences were collectively associated with group differences in Slow versus Fast Sequencing scores is uncertain. If nonlexical reading is related to temporal processing and lexical to sequencing performance, this would explain why both word types would be necessary to collectively effect group differences on Slow-Fast Sequencing. It seems more likely, however, that nonlexical/nonword reading is partially associated with Sequencing (phonologic dyslexics Fast Sequencing is significantly lower than their Fast Same-Different) and lexical/irregular word reading with combined Fast and Sequencing effects. Their Fast Sequencing is significantly lower than their Slow Sequencing, but they scored perfectly on Fast Same-Different; so, rapid tone presentation alone is not associated with lexical reading. In other words, both lexical and nonlexical reading are affected by collective Fast and Sequential presentation factors, as opposed to Fast or Sequential presentations. Clearly, however, nonlexical reading is greatly affected by the speed of tone presentation alone (both Fast Sequencing and Fast Same-Different were low), although Sequencing with rapid presentations was the most difficult.
DISCUSSION

Several findings from this study may be useful in understanding the relations between auditory processing and reading:

1. Poor lexical readers have poor fast auditory sequencing skills and lexical reading is associated with auditory sequencing skills.
2. Poor nonlexical reading is associated with generally poor performance on auditory temporal tasks, demonstrating particularly poor performance when tones are presented rapidly.
3. Nonword reading is robustly related to the performance on the Fast Same-Different tone tasks.

Given these findings, it is acknowledged that although temporal order and rapid temporal processing skills overlap, they are different processes that are differentially related to lexical and nonlexical reading. As such, we may wish to refrain from referring to poor performance on rapidly presented tone tasks requiring temporal order recall as deficits of "rapid temporal order" perception, as "rapid" and "order," albeit associated, require different processing mechanisms. In addition, when discussing poor sequencing/serial order recall in poor readers, we must acknowledge whether they are phonologic or surface dyslexics since this type of processing appears to be associated with lexical reading in particular.

Because poor nonlexical readers have generally poor performance across tone tasks whereas poor lexical readers do not, despite their similar performance on all TOMAL (memory and learning) subtests, it is likely that the auditory task performance has an auditory basis. Because phonologic dyslexics showed generally poor performance across tone tasks (although particularly poor with rapid presentations), we must ask what auditory component was similar across the tone tasks. The tone frequencies, brevity of stimuli, and temporal presentations were similar across these tasks. For lack of a better phrase, their difficulty might be described as a temporal processing deficit.

Why sequencing performance is related only to lexical reading remains to be determined, as does the finding that performance on the Fast Same-Different task is robustly related to nonword reading.

It may be argued that extra-auditory deficits could underlie performance on the tone tasks (e.g., underdeveloped strategies for the tasks). However, it is difficult to see how a cognitive deficit might contribute to the observed performance patterns. First, from the standpoint of dyslexic subtypes, phonologic and surface dyslexics did not significantly differ on any of the TOMAL subtests but did show very different patterns on the tone tasks, raising the likelihood of underlying differences in auditory processing. More generally speaking, given evidence for maturational delay of specific auditory processes (e.g., delay for low, as opposed to high, tone frequency perception within temporal tasks) in relation to other auditory processes in children without learning difficulties/dyslexias (Irwin et al, 1985; Werner, 1996), it is acknowledged that specific auditory delay might occur irrespective of underdeveloped cognitive strategies for these tasks. This, coupled with evidence of maturational delay for auditory temporal processes in poor readers (nonspeech tasks with or without evidence of abnormalities within the auditory system) (Welsh et al, 1980; Musiek et al, 1994; Nittrouer and Crowther, 1998), calls for consideration of possible audiological causes of temporal processing performance patterns.

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