# Sound–Symbol Learning in Children with Dyslexia

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## Abstract

This study evaluated the effect of sound–symbol association training on visual and phonological memory in children with a history of dyslexia. Pretests of phonological and visual memory, a sound–symbol training procedure, and phonological and visual memory posttests were administered to children with dyslexia, to children whose dyslexia had been compensated through remedial training, and to age- and reading level–matched comparison groups. Deficits in visual and phonological memory and memory for sound–symbol associations were demonstrated in the dyslexia group. For children with dyslexia and children whose dyslexia had been remediated, the sound–symbol training scores were significantly associated with word and pseudoword reading scores and were significantly lower than those of the comparison groups. Children with dyslexia and children whose dyslexia had been compensated showed significantly less facilitation of phonological memory following the training than did typical readers. Skilled readers showed some reduction in accuracy of visual memory following the training, which may be the result of interference of verbalization with a predominantly visual task. A parallel decrease was not observed in the children with dyslexia, possibly because these children did not use the verbal cues. Children with dyslexia and children whose dyslexia had been compensated seemed to have difficulty encoding the novel sounds in memory. As a result, they derived less phonological memory advantage and less visual memory interference from the training than did typical readers. Children in the compensated dyslexia group scored lower on sound–symbol training than their age peers. In other respects, the scores of these children were equivalent to those of the typically reading comparison groups. Children in the compensated dyslexia group exhibited higher phonological rehearsal, iconic memory, and associative memory scores than children in the dyslexia group. Implications for the remediation of dyslexia are discussed.


Children with reading disabilities often experience extreme difficulty in learning the letter–sound correspondences that constitute basic decoding skills (Gillingham & Stillman, 1987; Siegel, 1986, 1993; Siegel & Faux, 1989; Snowling, 1980; Spector, 1995; Stanovich, 1986, 1988). Tests of decoding (i.e., reading of nonwords) are considered among the best diagnostic measures of dyslexia (e.g., Foorman, Francis, Fletcher, & Lynn, 1996; Siegel & Heaven, 1986; Siegel & Ryan, 1988, 1989; Stanovich & Siegel, 1994).

Many contemporary researchers attribute the sound–symbol association difficulties of individuals with dyslexia to phonological awareness (i.e., perception) and encoding (i.e., memory) limitations (Felton & Pepper, 1995; Foorman, Francis, Fletcher, Schatschneider, & Mehta, 1998; Gathercole & Baddeley, 1989, 1990a, 1990b; McDougall, Hulme, Ellis, & Monk, 1994; Torgesen et al., 1990; Torgesen et al., 2001; Vellutino & Scanlon, 1982; Walton, Walton, & Felton, 2001). Verbal memory span limitations in children with dyslexia have been demonstrated on letter-string repetition and memory scanning tasks (Farnham-Diggory & Gregg, 1975; O'Shaughnessy & Swanson, 1998; Siegel & Ryan, 1988; Spring & Capps, 1974). These verbal memory span tasks are thought to reflect phonological encoding ability (Gathercole & Baddeley, 1989, 1990a, 1990b; Gathercole et al., 1991; Hulme & Tordoff, 1989; Torgesen, 1988; Torgesen, Wagner, & Rashotte, 1994).

There is some empirical evidence that part of the disability may be in visual perception and memory for the forms of letters or their position in a sequence (Badian, 1998; Cornoldi, Rigoni, Tressoldi, & Vio, 1999; Eden, Stein, Wood, & Wood, 1995; Morrison, Giordani, & Nagy, 1977; Slaghuis, Lovegrove, & Davidson, 1993). Visual limitations associated with dyslexia have also been attributed to perceptual (Badcock & Lovegrove, 1981; DiLollo, Hansen, & McIntyre, 1983; Eden et al., 1995; Enns, Bryson, & Roes, 1995; Galaburda & Livingstone, 1993; Slaghuis et al., 1993) and memory processes (Corkin, 1974; Enns et al., 1995; Morrison et al., 1977; Spring & Capps, 1974; Swanson, 1978, 1983, 1984).

The concept of visual perceptual deficits in dyslexia has lately been considered "thoroughly debunked" (Stanovich, 1988, p. 601). However, there is evidence of an abnormality called *visible persistence* in the early stages of processing of transient visual stimuli in individuals with dyslexia. This perceptual deficit could result in impaired visual memory, especially for items in sequences, and could interfere with reading by generating overlapping or superimposed images of letters (Di-Lollo et al., 1983; Eden et al., 1995; Farmer & Klein, 1995; Klein & Farmer, 1995; Slaghuis et al., 1993). Observations about visible persistence and other studies of orthographic processing in individuals with dyslexia (Badian, 1998; Cornoldi et al., 1999; Foorman et al., 1996; Siegel, Share, & Geva, 1995) have led to a resurgence of interest in visual memory and imagery as they affect reading.

Visual memory deficits in children with dyslexia have mainly been demonstrated in studies of *visual memory span* (Corkin, 1974; Morrison et al., 1977; Noelker & Schumsky, 1973; Senf & Freundl, 1971; Spring & Capps, 1974; Swanson, 1978, 1983, 1984). Some studies of visual memory have shown no impairment of immediate memory (Huba & Vellutino, 1990; Spring & Capps, 1974; Swanson, 1978, 1984, 1986). For example, in two visual memory studies, children with reading disabilities had equal or better memory for the last items in a sequence (iconic memory). Their memory was only impaired for earlier list items (Spring & Capps, 1974; Swanson, 1984).

The first hypothesis tested in this study was that in comparison to children with typical reading skills, children with dyslexia have deficits in visual memory for pseudoletters and in phonological memory for pseudowords. Phonological and visual memory span tests were used to assess this hypothesis. A test of immediate visual (iconic) memory was also administered. The second hypothesis tested in this study was that scores on both visual and phonological memory span tests would be positively correlated with reading scores.

In the experimental population were some children who had a history of dyslexia but who had developed reading skills above the 25th percentile as a result of remedial reading instruction. There has been little research to date concerning children whose reading difficulties have been compensated (Gallagher, Laxon, Armstrong, & Frith, 1996). The presence of these children in the sample made it possible to assess the possibility that basic cognitive deficits typically documented in readers with dyslexia might cease to exist if remediation is successful.

Deficits in the integration of verbal and visual memory codes have been demonstrated in children with a reading disability (Birch & Belmont, 1964; Ceci, Lea, & Ringstrom, 1980; Torgesen, 1978–1979; Vellutino, Steger, Harding, & Philips, 1975; see also Vellutino & Scanlon, 1982, for a review). Memory studies using named and unnamed stimuli (Katz, Shankweiler, & Liberman, 1981; Torgesen & Murphey, 1979; Vellutino & Scanlon, 1982) have indicated that skilled readers have a facility for additive combination of visual and verbal cues relative to readers with dyslexia. The third hypothesis tested in this study was that children with dyslexia have deficits in memory span for newly learned sound–symbol associations in comparison with typical readers.

Deficits in phonological perception and memory (for letter sounds) and visual perception and memory (for letter forms) may constrain the learning of sound–symbol associations (Mauer & Kamhi, 1996). Associative memory deficits in children with dyslexia may, therefore, be the direct result of verbal and visual deficits. Alternatively, deficits in associative memory may represent a separate area of impairment, not causally related to phonological or visual deficits. To clarify this point, the fourth hypothesis tested in this study was that visual and phonological memory spans would be positively correlated with memory span scores for newly learned sound–symbol correspondences in both typical readers and readers with dyslexia.

The hypothesis that learning the names for symbols would increase memory span for the names and for the symbols in typical readers but not in children with dyslexia was also tested. Swanson (1986) reported that sound–symbol association training actually interfered with recall in children with dyslexia. In a summary of several of his own studies dealing with verbal and visual coding processes in children with and without reading disabilities, Swanson (1986) concluded that children of average intelligence who have dyslexia fail to use multiple codes in an additive fashion in memory tasks. Swanson's studies showed that label training increases memory for visual forms in skilled readers but seems to reduce recall in children with learning disabilities (Swanson, 1978, 1983, 1984). If children with dyslexia do not derive a memory benefit from using multiple codes, then perhaps the sound–symbol training aspect of phonics instruction only confuses them and interferes with their reading skill development.

The sixth hypothesis tested in this study was that in comparison to children with typical reading skills, children with dyslexia would show lower recall of items at the beginning of visual and phonological sequences but similar recall of items at the end of sequences. Difficulties with phonological encoding are often most profound for items at the beginning of a sequence, representing a specific problem with phonological rehearsal (Baddeley, 1986). This is called a *serial position effect*. Serial position effects can demonstrate strengths and weaknesses in particular memory strategies. Strong memory for beginning list items (*primacy*) represents the effective use of phonological rehearsal. Weak memory for these items suggests impaired rehearsal. Proficient recall of end items (*recency*) may reflect the duration of echoic memory, and weak recall of these items may represent auditory confusion with earlier items (*retroactive interference*).

## Method

### Participants

Participants were volunteers from two private schools. One school was Kenneth Gordon School, a private elementary school for students with severe reading disabilities. The other school was Pacific Academy, a Christian private school with elementary and secondary divisions. Thirty-one students from Kenneth Gordon School (ages 8 years 1 month to 13 years 1 month) and 31 students from Pacific Academy (ages 6 years 9 months to 12 years 5 months) were tested. The Kenneth Gordon School students all had histories of severe reading disabilities. Some of the students who had entered Kenneth Gordon School with a history of reading disability as defined in this study, after a year or more of intensive remedial training, scored sufficiently high on the Word Reading subtest of the *Wide Range Achievement Test–Third Edition* (WRAT-3; Wilkinson, 1993) and the *Woodcock Reading Mastery Test–Revised* (WRMT-R; Woodcock, 1987) Word Attack subtest that they were classified as the compensated dyslexia group (see Table 1).

The children with dyslexia had WRAT-3 Word Reading subtest or WRMT-R Word Attack subtest pseudoword reading scores at or below the 26th percentile. The children whose dyslexia had been compensated had WRAT-3 Word Reading subtest scores and WRMT-R Word Attack subtest scores at or above the 26th percentile but had entered the remedial language program with measured reading scores below that level. Comparison participants had scores on both reading tests at or above the 35th percentile and no history of dyslexia. All participants had IQ scores in the average range (80 or higher) as indicated in their psychoeducational test records or measured by the *Slosson Intelligence Test* (Slosson, 1981).

Each participant with dyslexia and each participant whose dyslexia had been compensated was assigned a specific age and a specific reading level match (matched for raw score on the WRAT-3) from among the typical readers. Thus, there were six groups:

1. children with dyslexia (D);
2. typical readers who were age matches for the children with dyslexia (D-A);
3. typical readers who were reading level matches for the children with dyslexia (D-RL);
4. children whose dyslexia had been compensated (C);
5. typical readers who were age matches for the C group (C-A); and
6. typical readers who were reading level matches for the C group (C-RL; see Table 1).

Some students who were typical readers were used as matches in more than one comparison group, resulting in some overlap of groups.

### Experimental Tasks

For all participants, the phonological pretest was administered first, then the iconic memory pretest, and then the visual memory span pretest. The sound–symbol association training followed the pretests. Then the phonological posttest was administered, followed by the iconic memory posttest, and then the visual memory span posttest.

**Phonological Memory Test.** The test of phonological memory (PM) span was based on a nonword repetition measure described by Gathercole and Adams (1993) and Gathercole and Baddeley (1989). One hundred twelve single-syllable, pronounceable pseudowords were used for the pretest, and 10 of these pseudowords were used for the posttest. The memory span task consisted of arrangements of pseudowords into sequences of one, two, three, four, five, six, and seven elements. The stimuli for the nonword tests were recorded on a cassette tape at a speed of 1 psuedoword per second. List lengths began at one and increased to seven. There were four lists at each list length. At the end of each list, a pause and a high tone signaled that the child had up to 11 seconds to reproduce the list. The posttest was similar to the pretest but consisted of sequences constructed by random selec-

**TABLE 1**
Demographic and Reading Skill Data on All Groups

| | D[a] | | D-A[b] | | D-RL[c] | | C[d] | | C-A[e] | | C-RL[f] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *MD* | *SD* | *M* | *SD* |
| Age | 10.73 | 1.27 | 10.70 | 1.26 | 8.11 | 1.48 | 10.76 | 1.27 | 10.46 | 1.16 | 8.81 | 1.75 |
| Grade | 4.58 | 1.62 | 4.50 | 1.24 | 2.08 | 1.24 | 5.21 | 1.44 | 4.26 | 1.15 | 2.79 | 1.48 |
| WRAT-3 | | | | | | | | | | | | |
| Percentile | 23.58 | 20.17 | 94.76 | 6.56 | 72.42 | 17.16 | 75.74 | 15.94 | 94.95 | 6.76 | 92.47 | 9.24 |
| Raw score | 30.75 | 4.50 | 46.25 | 5.46 | 33.08 | 7.23 | 40.21 | 4.32 | 45.36 | 4.96 | 40.31 | 5.00 |
| WRMT-R | | | | | | | | | | | | |
| Percentile | 24.58 | 14.93 | 82.17 | 16.62 | 72.42 | 17.16 | 67.79 | 15.13 | 81.89 | 16.86 | 81.81 | 17.78 |

*Note.* D = children with dyslexia; D-A = controls matched to D group by age; D-RL = controls matched to D group by reading level; C = children whose dyslexia has been compensated; C-A = controls matched to C group by age; C-RL = controls matched to C group by reading level. WRAT-3 = *Wide Range Achievement Test–Third Edition* (Wilkinson, 1993); WRMT-R = *Woodcock Reading Mastery Test–Revised* (Woodcock, 1987).
[a]*n* = 12; 8 boys, 4 girls. [b]*n* = 12; 9 girls, 3 boys. [c]*n* = 12; 10 girls, 2 boys. [d]*n* = 19; 11 girls, 8 boys. [e]*n* = 19; 13 girls, 6 boys. [f]*n* = 19; 12 girls, 7 boys.

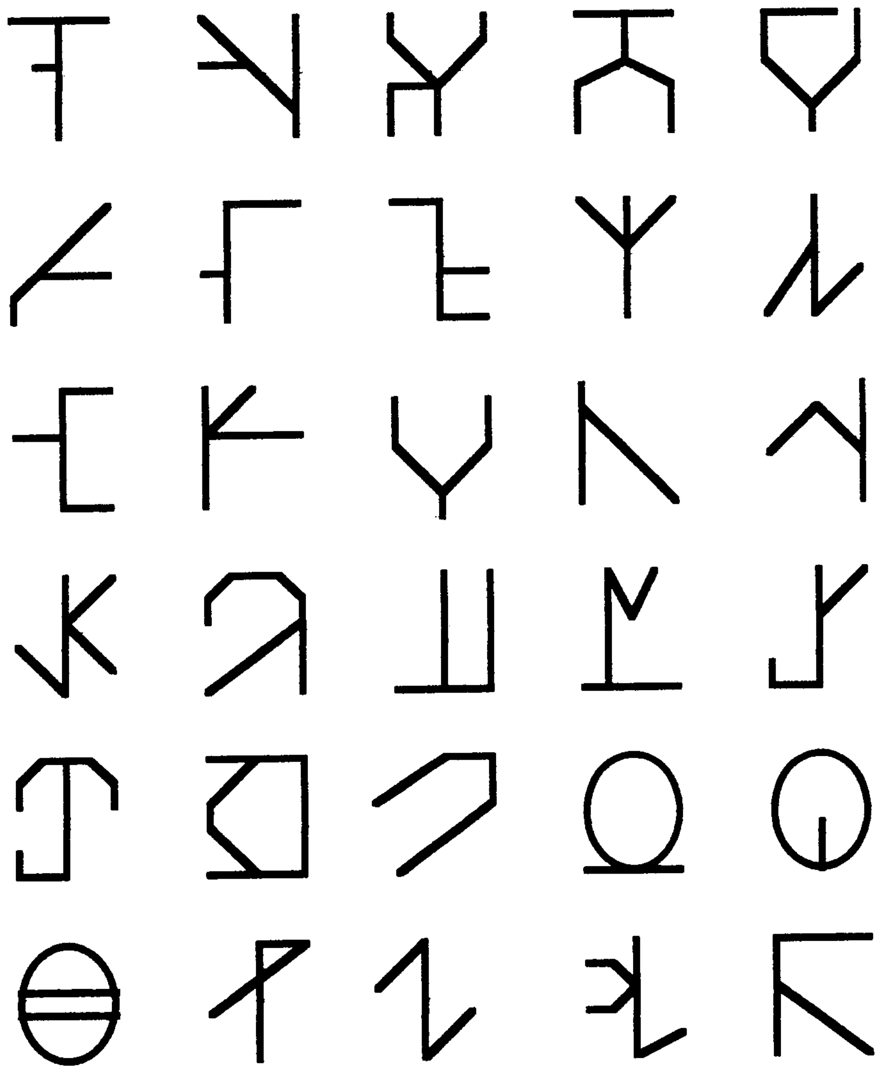

**FIGURE 1.** Pseudoletters used in the visual memory tests. *Note.* From "Location Confusions in Visual Information Processing," by P. Dixon and L. Twilley, 1988, *Canadian Journal of Psychology,* 42, pp. 378–394. Copyright 1988 by Canadian Psychological Association. Adapted with permission.

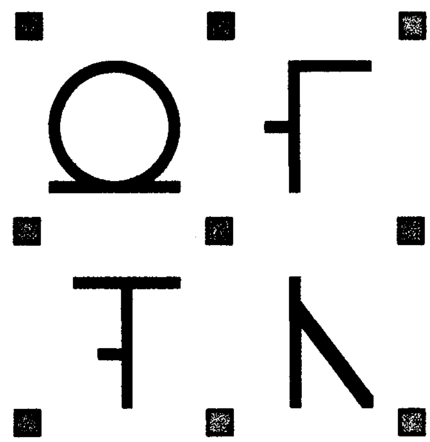

**FIGURE 2.** A sample array as shown on the computer screen. *Note.* From "Location Confusions in Visual Information Processing," by P. Dixon and L. Twilley, 1988, *Canadian Journal of Psychology,* 42, pp. 378–394. Copyright 1988 by Canadian Psychological Association. Adapted with permission.

tion with replacement from the 10 pseudowords used in the training intervention, so there were many fewer to remember.

**Iconic Memory Test.** This test used graphic displays on a computer monitor to assess iconic visual memory and reaction time. Thirty nonmeaningful simple line drawings (*pseudoletters;* Dixon & Twilley, 1988) were used as visual stimuli in this test (see Figure 1). Two-by-two grids of these pseudoletters were shown on a computer screen for 2 seconds (see Figure 2). A MacIntosh LC III computer and VScope software were used. Following presentation of each grid, a new grid was presented on the computer screen that contained only a single probe character in one of the grid positions. The other boxes in the grid were empty. The participant's task was to determine whether the probe character was contained in the same position as in the previous grid. The participant pressed keys on the computer keypad marked *there* and *not there* to indicate presence or absence of the target characters. The trials were presented in the same random order for each participant. The child's choices and the correct choices were recorded by the Vscope software in an internal data file. Latency scores were also recorded by the computer in this data file.

For the posttest, the four-element grids were constructed by selection from the 10 pseudoletters selected for the posttest and used in the training intervention (see Figure 3). Pre- and posttesting were conducted in blocks of 20 trials.

**Visual Memory Span Test.** The visual memory span task was based on one used by Katz, Shankweiler, and Liberman (1981). The 30 nonmeaningful simple line drawings used for the iconic memory test were used in this test as well. This test was also presented on a MacIntosh LC III computer, using Vscope software. Pseudoletters were arranged into sequences of two, four, and six elements. Elements in the sequences were paired so that two pseudoletters appeared at a time, each pair appearing in the center of the screen at a rate of about 1 pair per second. Each trial consisted of a sequence followed by a colored probe character. The participant's task was to determine whether the probe character had been contained in the sequence. Each participant completed a block of 20 trials, including 5 two-element lists, 10 four-element lists, and 5 six-element lists for both the pretest and the posttest. For the posttest, the sequences were constructed by selection from the 10 pseudoletters selected for the training procedure and the posttest. Posttesting was also conducted in blocks of 20 trials.

To calculate serial position scores, only sequences of four and six visual elements were used. The number of correct responses to probes corresponding to pseudoletters in the beginning (first pair), middle (second pair), and end (last pair) of the sequence were recorded. These scores were then converted according to the following equation:

$$\frac{\text{number of correct responses}}{\text{maximum possible correct}} \times 10 = \text{serial position score}$$

This allowed the recording of five dependent measures for each temporal test: total number correct, number of primacy items (i.e., first shown stimuli in each sequence) correct, number of middle items correct, number of recency items (i.e., last shown stimuli in each sequence) correct, and response latency.

## *Training Procedure*

A training procedure followed the three tasks. Ten of the pseudoletters and 10 of the pseudowords were selected for this test. Children were taught to associate each visual element with a specific phonological element; that is, the invented letters used in the visual memory span test were assigned names from the list of nonwords used in the nonword repetition test (see Figure 3). Items were presented in the same order for all participants.

Pictures of shapes on cards were presented and names supplied in iterative cycles either until the participant was able to name all of the stimuli in two complete presentations of the deck of 10 symbols or until the entire deck had been presented 20 times. The experimenter presented the stimuli on 3 × 5 inch index cards, in the first two presentations supplying the name ("This one is called . . ."). After the first two presentations, the experimenter waited a few seconds to allow the child to supply the name, then requested the name of the stimulus ("What sound goes with this shape?"). The experimenter provided the name if the child was unable to do so after 5 seconds ("This is . . .")

The number of cycles necessary to achieve the criterion level of mastery or the number of names mastered in 20 repetitions of the deck was recorded on the phonological memory coding sheets. The training score recorded represents the average number of names learned per one repetition of the deck.

# Results

## *Question 1*

Do children with a history of dyslexia have deficits in phonological or visual memory relative to chronological and reading age–matched children with typical reading skills?

**Phonological Memory.** To test the hypothesis that children with reading disabilities have deficits in phonological or visual memory relative to chronological and reading age–matched children with typical reading skills, the scores of D, C, and control group children on visual and phonological tasks were compared. The mean scores of D, C, and their respective comparison groups on the tasks are shown in Table 2.

Group mean pretest and posttest scores on memory measures for groups D and C were compared to the group mean scores of the D-A and D-RL and C-A and C-RL comparison groups, respectively, with a repeated measures analysis of variance (ANOVA). The 3 × 2 repeated measures analyses that were conducted represent three reading groups and two times of testing (pre- and posttest). Six of the 3 × 2 comparisons were computed, comparing D to D-A and D-RL and comparing C to C-A and C-RL for the phonological tests, the visual iconic memory tests, and the visual temporal memory tests. Post hoc Tukey HSD tests were used for the three group comparisons. The mean memory scores of group D were also compared to those of group C by 3 × 2 repeated measures ANOVA of D and C groups, and all matched typical readers participating in the study (see Table 2).

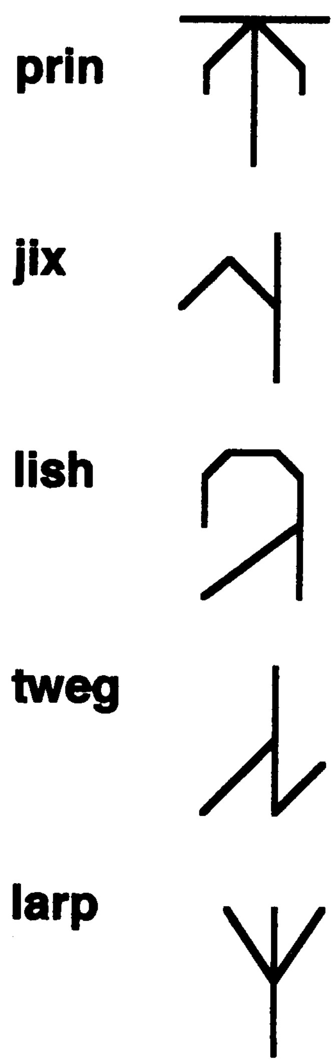


**FIGURE 3.** Symbols used in the training intervention and posttests. *Note.* From "Location Confusions in Visual Information Processing," by P. Dixon and L. Twilley, 1988, *Canadian Journal of Psychology*, 42, pp. 378–394. Copyright 1988 by Canadian Psychological Association. Adapted with permission.

**TABLE 2**
Comparison of Dyslexia Groups and Matched Controls on Phonological and Visual Memory Variables

| | D | | D-A | | D-RL | | C | | C-A | | C-RL | | MC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***MD*** | ***SD*** | ***M*** | ***SD*** |
| Phonological memory | | | | | | | | | | | | | | |
| Pretest | 72.83 | 27.89 | 89.75 | 17.16 | 78.17 | 13.74 | 83.84 | 16.91 | 90.89 | 17.10 | 83.74 | 14.51 | 86.33 | 18.11 |
| Posttest | 90.58 | 29.73 | 143.25[a] | 44.59 | 118.25 | 14.67 | 112.58 | 35.55 | 131.11 | 40.99 | 112.58 | 20.59 | 122.97 | 41.71 |
| Iconic memory | | | | | | | | | | | | | | |
| Pretest | 12.17 | 2.79 | 15.08 | 1.89 | 13.75 | 2.80 | 14.74 | 1.88 | 15.26 | 1.88 | 13.95 | 2.70 | 14.17[a] | 2.51 |
| Posttest | 11.67 | 3.11 | 13.50[a] | 1.51 | 12.75 | 2.09 | 13.00 | 3.40 | 13.68 | 1.77 | 13.32 | 2.14 | 13.20 | 1.92 |
| Visual memory span | | | | | | | | | | | | | | |
| Pretest | 12.91 | 1.45 | 14.67 | 1.56 | 14.25 | 2.14 | 13.68 | 2.47 | 15.11 | 1.63 | 14.68 | 1.77 | 14.53 | 1.85 |
| Posttest | 13.33 | 2.50 | 14.50 | 2.43 | 13.25 | 1.82 | 14.26 | 2.56 | 13.63 | 2.11 | 13.58 | 2.19 | 13.67 | 2.02 |
| Training score | 0.43 | 0.26 | | | | | 0.66[a] | 0.22 | | | | | 0.89[a] | 0.37[b] |
| Visual response latency | 1,819.42 | 498.72 | 1,805.45 | 427.88 | 2,198.64 | 327.26 | 1,742.50 | 392.00 | 1,835.80 | 381.30 | 2,099.40 | 373.30 | | |

*Note.* D = children with dyslexia; D-A = controls matched to D group by age; D-RL = controls matched to D group by reading level; C = children whose dyslexia has been compensated; C-A = controls matched to C group by age; C-RL = controls matched to C group by reading level; MC = all matched controls.
[a]Significantly different from the score obtained by the D group on the same test. [b]Significantly different from the score obtained by the C group on the same test.

On the phonological measures, repeated measures 3 × 2 ANOVA comparison of phonological pretest and posttest scores for group D with D-A and D-RL showed a significant main effect for group, $F(1, 33) = 6.22$, $p = .005$, ES = .27. The post hoc Tukey HSD test showed that the mean phonological pretest score of the D group was not significantly lower than the corresponding scores for either the D-A or the D-RL groups (see Table 2). However, relative to the D-A group, D group readers scored significantly lower on the phonological posttest, $p = .001$ (see Table 2). Therefore, in this investigation children in the D group did demonstrate significant deficits in phonological memory relative to D-A children on the phonological posttest, although not on the phonological pretest scores.

In comparison to younger students matched for reading level, D group students did not have significantly lower mean scores on either the phonological pretest or the phonological posttest (see Table 2). There were, however, significant differences between the D group and the D-RL group on all of the phonological posttest serial position variables in a 3 × 2 repeated measures comparison (see Table 3). A repeated measures 3 × 2 ANOVA of phonological pretest and posttest primacy scores showed a significant main effect for group, $F(2, 33) = 3.38$, $p = .046$, and a significant interaction effect, $F(2, 33) = 5.17$, $p = .011$, ES = .239. D group children showed a significant deficit in phonological posttest primacy scores representing pseudowords in the beginning of posttest memory lists in comparison to their age peers, $p = .05$, and to their reading level peers, $p = .002$, according to Tukey post hoc analysis (see Table 3). Scores for pretest primacy did not differ significantly among these groups (see Table 4).

Similarly, a repeated measures ANOVA of phonological pretest and posttest middle position scores showed a significant main effect for group, $F(2, 33) = 4.55$, $p = .016$, and a significant interaction effect, $F(2, 33) = 4.40$, $p = .02$. Children with dyslexia showed a significant deficit in phonological posttest middle position scores in comparison to their age peers, $p = .005$, and their reading level peers, $p = .04$, according to Tukey post hoc analysis (see Table 3).

Repeated measures ANOVA of phonological pretest and posttest recency scores showed a significant interaction effect, $F(2, 33) = 4.66$, $p = .016$, but no significant group main effect. In the C group and in all control groups, the recency effect that was evident on the pretest was reduced or eliminated on the posttest. This did not occur in the D group. Children in this group showed a significant recency effect on both pretest and posttest (i.e., significant elevation of recency score relative to middle position score). Children with dyslexia showed a significant deficit in phonological posttest recency scores in comparison to their age peers, $p = .032$, and their reading-level peers, $p = .003$, according to Tukey post hoc analysis (see Table 3), ES = .22 for the interaction. Thus, children in the D group did show significant deficits in phonological memory relative to D-RL readers with respect to individual serial position scores but not on the phonological pretest and posttest total scores.

A repeated measures 3 × 2 ANOVA comparison of phonological pretest and posttest scores for the C group children with C-A and C-RL groups did not show a significant main effect for group (see Table 2). Furthermore, the C group did not show significant deficits at any of the phonological serial positions (see Tables 3 and 4). Children in the C group did not demonstrate significant deficits in phonological memory relative to C-A or C-RL groups.

**Visual Memory.** Although the D group had lower mean scores on all of the visual tests than either of the comparison groups, significant differences in mean visual memory scores were evident only between D group children and D-A group children on the

**TABLE 3**
Phonological Posttest Serial Position Scores by Groups

| | Primacy | | | Middle | | | Recency | | |
|---|---|---|---|---|---|---|---|---|---|
| Group | *M* | *SD* | *p*[a] | *M* | *SD* | *p*[a] | *M* | *SD* | *p*[a] |
| D | .71 | .25 | | .55 | .33 | | .60 | .27 | |
| D-A | .89 | .16 | .054 | .87 | .18 | .007 | .80 | .13 | .029 |
| D-RL | .98 | .05 | .004 | .79 | .16 | .033 | .87 | .12 | .006 |
| C | .94 | .10 | | .74 | .22 | | .72 | .23 | |
| C-A | .92 | .13 | *ns* | .80 | .20 | *ns* | .81 | .16 | *ns* |
| C-RL | .89 | .16 | *ns* | .73 | .24 | *ns* | .79 | .17 | *ns* |

*Note.* D = children with dyslexia; D-A = controls matched to D group by age; D-RL = controls matched to D group by reading level; C = children whose dyslexia has been compensated; C-A = controls matched to C group by age; C-RL = controls matched to C group by reading level.
[a]Significance scores for *t* test comparisons between disability groups and matched control groups.

iconic memory pretest (see Table 2). For children in the D group and D-A and D-RL groups, a repeated measures ANOVA of iconic memory pretest and posttest scores showed a significant main effect for group, $F(2, 35) = 4.37$, $p = .021$, ES = .21. According to Tukey post hoc analysis, D group readers scored significantly lower than their D-A peers on the iconic memory pretest, $p = .021$. The visual memory span pretest and posttest 3 × 2 analysis did not show a significant main effect for reading group.

A multivariate 3 × 2 ANOVA for the D group and both of its comparison groups also showed significant differences between the D group and the D-A group on the iconic memory pretest, $F(2, 34) = 3.47$, $p = .035$, and the visual memory span pretest, $F(2, 34) = 3.28$, $p = .049$, according to post hoc Tukey analysis. In summary, children with reading disability demonstrated visual iconic memory deficits relative to age peers with typical reading skills but not relative to younger typical readers matched for reading level. They did not show statistically significant deficits in visual memory span relative to either comparison group.

There was a significant main group effect on mean visual response latency, $F(2, 35) = 3.32$, $p = .048$. However, post hoc Tukey analysis did not show any significant two-group differences. Younger children were generally slower to respond manually to the visual probes than older ones, regardless of reading ability. Children with dyslexia scored similar to their age peers on visual response latency.

Children in the C group did not demonstrate significant iconic memory deficits relative to either of the typically reading comparison groups (age or reading level matches). The C group did not score significantly lower than either C-A or C-RL groups on the visual memory span tests. There was a significant difference between the C group and the C-RL group on visual response latency, $F(2, 56) = 4.45$, $p = .016$, ES = .17. The mean visual response speed of the older children was higher than that of the younger reading level–matched group.

In some of the comparisons, visual memory scores were significantly correlated with age. In the typical readers, the iconic memory pretest score was significantly associated with age, $r(30) = .65$, $p < .001$, as was the iconic memory posttest score, $r(30) = .41$, $p = .025$, and the visual memory span pretest score, $r(30) = .38$, $p = .039$. For the C group children, the iconic memory pretest was significantly associated with age, $r(19) = .58$, $p = .009$. There was significant correlation of age and visual response latency, reflecting the fact that the youngest children were slower to respond to the computer. The analysis of covariance (ANCOVA) procedure was therefore used for the analysis of visual memory, using age as a covariate. This increased the level of significance of group differences in the groups that were matched by age. For the D group students and matched D-RL students, the use of the covariate analysis resulted in some group mean differences that were significant at the 5% level. Significant differences were noted for the iconic memory pretest, $F(1, 23) = 5.15$, $p = .034$, and the iconic memory posttest, $F(1, 23) = 4.65$, $p = .043$. D group children scored significantly lower than the D-RL comparison group on both iconic memory measures. Phonological memory span scores were not significantly associated with age in the groups tested.

The mean memory scores of the D group readers were compared to those of C group readers by 3 × 2 repeated measures ANOVAs of D and C groups and all typical readers participating in the study (see Table 2). C group children had higher mean scores than D group children on all the visual memory tests, but only on the iconic memory pretest was the difference significant. A repeated measures ANOVA showed a significant group effect, $F(2, 58) = 3.80$, $p = .028$, ES = .12. The score of the D group was significantly lower than that of the C group, $p = .014$, by a Tukey test.

The D group also had a lower mean score on the phonological memory posttest than the C group. The main effect for group was $F(2, 58) = 3.11$, $p = .052$. According to post hoc Tukey analysis, the D and C groups were significantly different, $p = .039$. The C group scored significantly higher than the D group on phonological primacy on both the pretest and the posttest, $F(2, 58) = 7.33$, $p = .023$ and $p = .001$, respectively, ES = .20.

## *Question 2*

Are scores on the measures of phonological or visual memory significantly associated with reading skills in

**TABLE 4**
Phonological Pretest Serial Position Scores by Groups

| | Primacy | | Middle | | Recency | |
|---|---|---|---|---|---|---|
| Group | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| D | .52 | .39 | .45 | .33 | .64 | .36 |
| D-A | .81 | .16 | .65 | .17 | .69 | .15 |
| D-RL | .57 | .35 | .40 | .27 | .52 | .33 |
| C | .79 | .17 | .59 | .15 | .71 | .19 |
| C-A | .79 | .15 | .64 | .17 | .72 | .19 |
| C-RL | .76 | .17 | .55 | .18 | .64 | .19 |

*Note.* All *t* test ccomparisons between disability groups and matched control groups were nonsignificant. D = children with dyslexia; D-A = controls matched to D group by age; D-RL = controls matched to D group by reading level; C = children whose dyslexia has been compensated; C-A = controls matched to C group by age; C-RL = controls matched to C group by reading level.

children with a history of dyslexia or in chronologically and reading age–matched children with typical reading skills? To determine whether measures of phonological or visual memory were significantly associated with reading skills in children in the D and C groups or in the control groups, partial correlations (controlling for age) were employed. To obtain a score for all control participants, data from all matched comparison groups were combined. Mean scores on the visual and phonological measures were compared to mean scores on the reading tests. Significant correlations between some of the measures and the reading scores were obtained, as listed in Tables 5 and 6. When all participants in the study were considered as a group, phonological pretest and postest scores and serial position scores for items in the primacy and middle positions of memory lists were significantly associated with both word and pseudoword reading. Considering only the typical readers, all phonological pretest serial position scores were significantly associated with word reading and pseudoword reading (see Tables 5 and 6).

**TABLE 5**
Significant Correlations Between Memory Variables and Reading Scores for All Participants ($N = 60$)

| | WRAT-3 | | WRMT-R | |
|---|---|---|---|---|
| **Memory variable** | *r* | *p* | *r* | *p* |
| Phonological memory | | | | |
| Pretest | | | | |
| Total | .28 | .033 | .36 | .005 |
| Primacy | .42 | .001 | .42 | .001 |
| Middle | .36 | .005 | .38 | .003 |
| Recency | *ns* | | *ns* | |
| Posttest | | | | |
| Total | .42 | .001 | .38 | .003 |
| Primacy | .34 | .007 | .33 | .009 |
| Middle | .35 | .006 | .38 | .003 |
| Recency | *ns* | | *ns* | |
| Iconic memory | | | | |
| Pretest | .37 | .003 | *ns* | |
| Sound–symbol training score | –.60 | .001 | .66 | .001 |

*Note.* WRAT-3 = *Wide Range Achievement Test–Third Edition*; WRMT-R = *Woodcock Reading Mastery Test–Revised.* Participants' scores on WRAT-3 and WRMT-R were significantly correlated, $r = .87$, $p = .001$. All visual memory span tests were nonsignificant, with the exception of the posttest primacy score, which was significantly correlated with the WRAT-3 ($r = .33$, $p = .01$).

**TABLE 6**
Significant Correlations Between Memory Variables and Reading Scores for Matched Groups of Typical Readers

| | WRAT-3 | | WRMT-R | |
|---|---|---|---|---|
| **Memory variable** | *r* | *p* | *r* | *p* |
| Phonological memory | | | | |
| Pretest | | | | |
| Total | .37 | .050 | .44 | .018 |
| Primacy | .57 | .001 | .46 | .012 |
| Middle | .55 | .002 | .46 | .013 |
| Recency | .63 | .001 | .58 | .001 |
| Visual memory span | | | | |
| Posttest | | | | |
| Primacy | .48 | .008 | *ns* | |
| Middle | .44 | .017 | .41 | .029 |
| Recency | *ns* | | *ns* | |
| Sound–symbol training score | –.36 | .055 | .41 | .026 |

*Note.* WRAT-3 = *Wide Range Achievement Test–Third Edition*; WRMT-R = *Woodcock Reading Mastery Test–Revised.* Participants' scores on WRAT-3 and WRMT-R were significantly correlated, $r = .79$, $p = .001$. All phonological posttest correlations were nonsignificant. All visual memory span pretest correlations were nonsignificant.

## *Question 3*

Do children with a history of dyslexia have deficits in memory span for letter–sound correspondences relative to chronologically and reading age–matched children with typical reading skills? ANOVAs of sound–symbol training scores were used to determine whether children with dyslexia had deficits in memory span for letter–sound correspondences relative to chronologically and reading age–matched children with typical reading skills. The scores for the sound–symbol association task were presumed to represent memory span for sound–symbol correspondences (see Table 7).

A three-group ANOVA showed a significant main effect for group, $F(2, 35) = 8.76$, $p = .001$, ES = .53. D group participants had significantly lower scores on training than either D-A children, $p = .001$, or D-RL children, $p = .025$, by post hoc Tukey analysis. Children with reading disability had deficits in memory span for novel letter–sound correspondences relative to chronologically and reading age–matched children with typical reading skills.

An ANOVA of sound–symbol training scores of the C group and its comparison groups showed a significant main effect for group, $F(2, 56) = 5.04$, $p = .01$, ES = .19. The C group's train-

**TABLE 7**
Comparison of Dyslexia Groups and Matched Controls on Memory Scores for Letter–Sound Correspondences

| | D | | D-A | | D-RL | | C | | C-A | | C-RL | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***MD*** | ***SD*** | ***M*** | ***SD*** |
| Pretest | | | | | | | | | | | | |
| Primacy | 5.27 | 2.41 | 6.83 | 1.80 | 6.83 | 2.17 | 6.00 | 2.83 | 7.16 | 1.80 | 7.37 | 2.00 |
| Recency | 9.09 | 3.02 | 9.16 | 1.95 | 8.33 | 2.46 | 8.33 | 2.43 | 9.21 | 1.87 | 9.21 | 1.87 |
| Posttest | | | | | | | | | | | | |
| Primacy | 4.77 | 2.36 | 5.83 | 3.26 | 4.79 | 3.10 | 5.92 | 2.66 | 6.05 | 2.68 | 5.79 | 2.89 |
| Middle | 6.36 | 5.04 | 9.17 | 2.89 | 5.83 | 5.15 | 5.79 | 5.06 | 6.84 | 4.78 | 7.37 | 4.52 |
| Recency | 8.18 | 3.37 | 9.17 | 1.95 | 7.08 | 3.34 | 7.89 | 3.03 | 8.16 | 2.99 | 8.16 | 2.99 |
| Training | .43 | .26 | .93 | .29 | .77 | .34 | .66 | .22 | 1.01 | .39 | .89 | .39 |

*Note.* D = children with dyslexia; D-A = controls matched to D group by age; D-RL = controls matched to D group by reading level; C = children whose dyslexia has been compensated; C-A = controls matched to C group by age; C-RL = controls matched to C group by reading level.

ing score was significantly lower than that of the C-A group by Tukey test, $p = .008$. C group children had deficits in memory span for novel letter–sound correspondences relative to C-A matched children. The C group did not score significantly lower than the C-RL group.

Participants whose dyslexia had been compensated did score significantly lower on sound–symbol training than a combined group of all the typical readers in the study, $F(2, 60) = 10.54$, $p < .001$, ES = .36. The mean training score for the C group was not significantly different from that of the D group in a 3 × 2 ANOVA. However, in a two-group comparison of D and C group participants, there was a significant difference in mean training scores when age was used as a covariate, $F(1, 37) = 7.52$, $p = .01$.

## *Question 4*

In children with a history of dyslexia, are memory span scores for sound–symbol correspondences related to visual and phonological memory scores? To determine whether memory spans for letter–sound correspondences were significantly related to visual and phonological memory scores, partial correlations (controlling for age) were used. Partial correlations between the phonological measures and sound–symbol training scores were not significant in the D group or in typical reading groups. Training scores were also not significantly associated with any of the visual measures in the D group. For typically reading students in Grade 1 (i.e., the D-RL group), training scores were significantly associated with phonological posttest primacy, $r(10) = .85$, $p = .002$, and phonological posttest recency, $r(10) = .79$, $p = .006$. Phonological memory may play a limiting role in memory for sound–symbol correspondences in very young but not in older children.

## *Question 5*

Do learned sound–symbol correspondences differentially affect visual and phonological memory for children with a history of dyslexia and their peers? To investigate the hypothesis that learned sound–symbol associations differentially influence visual and phonological memory for children with a history of dyslexia and their matched peers, the differential effects of the sound–symbol training were analyzed by a 3 × 2 repeated measures ANOVA. The three levels of group represented comparisons of the D group to each control group and then of the C group to each control group. The two levels of test were the pretest and the posttest. Interaction effects were analyzed by repeated measures ANOVA and ANCOVA using age as a covariate.

All groups had higher mean phonological posttest scores than mean phonological pretest scores. The main effects for pretest–posttest were significant for D and comparison groups, $F(1, 33) = 88.02$, $p < .001$, ES = .73, and for C and comparison groups, $F(1, 54) = 91.33$, $p < .001$, ES = .63. The phonological posttest was presumably easier for the children than the pretest because the pseudowords were familiar and because there were fewer of them in the posttests (only 10 as opposed to 112 for the pretest). There may also have been a facilitative effect of multiple coding among typical readers because phonological posttest scores are significantly associated with sound–symbol association scores for this group. The association of phonological posttest and training scores was not significant in the D group. Significant interaction effects were obtained for the phonological tests in comparisons involving the D group, $F(1, 33) = 6.22$, $p = .005$. The mean score increase from pretest to posttest was significantly less for the dyslexia group than for the matched comparison groups. Phonological pretest–posttest interaction effects were not significant in comparisons involving the C group.

Following the sound–symbol training procedure, mean iconic memory scores decreased. The main pretest–posttest effects for iconic memory were significant by 3 × 2 repeated measures ANOVA for D and comparison groups, $F(1, 33) = 4.68$, $p = .038$, and for C and comparison groups, $F(1, 54) = 13.10$, $p = .001$, ES = .20. Mean iconic memory posttest scores were lower than iconic memory pretest scores for all groups. The mean pretest–posttest difference observed in the D group alone was not significant when the scores were compared by ANOVA, ANCOVA, or *t* test. Following the sound–symbol association training, an ANOVA for visual memory span pretest and posttest scores did not show a significant mean score change for the D group and its comparison groups or for the C group and its comparison groups. There were no significant interaction effects for iconic memory or visual memory span.

## *Question 6*

Are serial position curves for visual and phonological memory spans significantly different for children with a history of dyslexia and their typically reading peers? To determine whether serial position curves for visual and phonological memory spans were significantly different for children with dyslexia and their typically reading peers, mean serial position scores for the D and C groups and a third group composed of all typically reading participants were compared. To obtain mean phonological serial position scores, a count of correct phonemes for beginning, middle, and end positions in the four-pseudoword lists was recorded for each child. The four-element lists were chosen because all but two of the participants received some score for this list length, but only two had no errors at this length. Phonological serial position curves are typically U-shaped, higher at the beginning and at the end and depressed in the middle. Phonological primacy scores theoretically reflect the use of cumulative rehearsal of beginning and middle list items. Recency scores represent the superiority of immediate auditory memory in the absence of interference. All groups showed phonological pretest serial position effects (see Table 4 and Figure 4), with some variations.

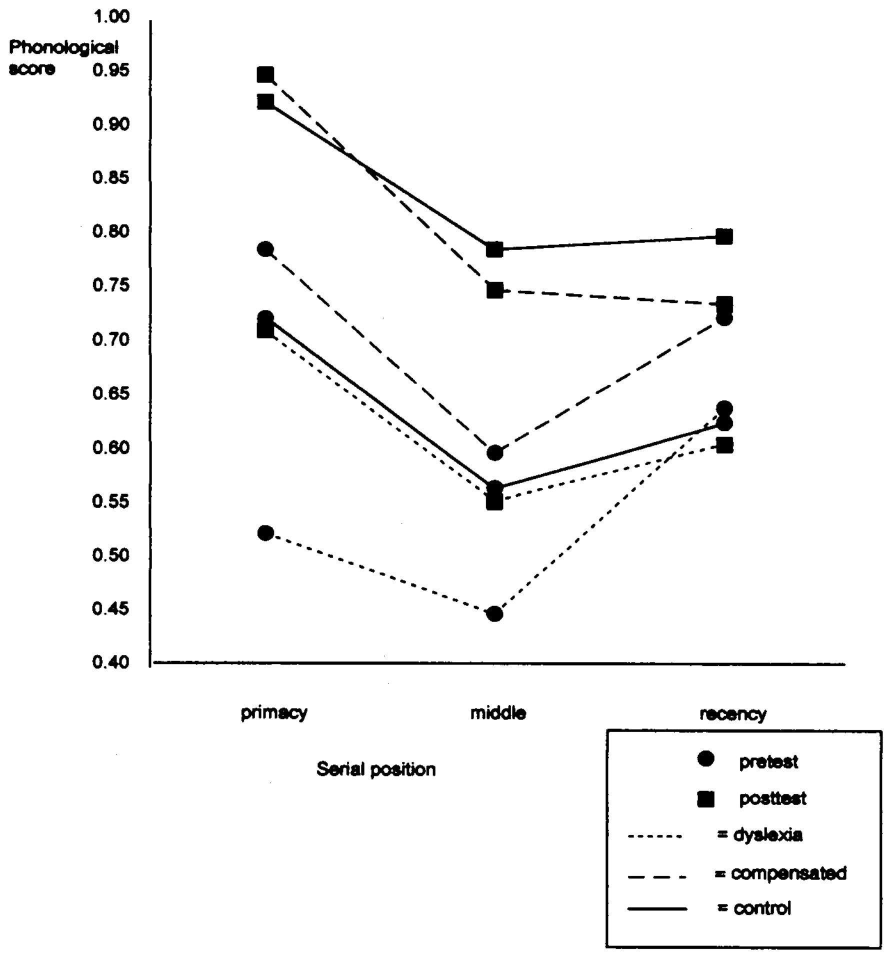


**FIGURE 4.** Phonological pretest and posttest serial position scores for all groups.

A repeated measures 3 × 2 ANOVA of phonological pretest and posttest primacy scores showed a significant main effect for group, $F(2, 33) = 3.38$, $p = .046$, and a significant interaction effect, $F(2, 33) = 5.17$, $p = .011$. D group children showed a significant deficit in phonological posttest primacy scores, representing pseudowords at the beginning of posttest memory lists, in comparison to both their age peers, $p = .05$, and their reading-level peers, $p = .002$, according to Tukey post hoc analysis (see Table 6). Scores for pretest primacy did not differ significantly among these groups.

Similarly, repeated measures ANOVA of phonological pretest and posttest middle position scores showed a significant main effect for group, $F(2, 33) = 4.55$, $p = .018$, and a significant interaction effect, $F(2, 33) = 4.40$, $p = .02$. Children with dyslexia showed a significant deficit in phonological posttest middle position scores in comparison to both their age peers, $p = .005$, and their reading-level peers, $p = .04$, according to Tukey post hoc analysis (as previously noted; see Table 3).

Repeated measures ANOVA of phonological pretest and posttest recency scores showed a significant interaction effect, $F(2, 33) = 4.66$, $p = .016$, but no significant group main effect. In the C group and the typical reading groups, the recency effect that was evident on the pretest was reduced or eliminated on the posttest. This did not occur in the D group (see Tables 3 and 4). Children with dyslexia showed a significant deficit in phonological posttest recency scores in comparison to both their age peers, $p = .032$, and their reading level peers, $p = .003$, according to Tukey post hoc analysis (as previously noted; see Table 3). C group children scored similarly to C-A and C-RL group children at all phonological serial positions. Phonological serial position curves of C group children, therefore, were not significantly different from those of C-A or C-RL group readers.

A repeated measures 3 × 2 ANOVA of phonological primacy scores of D and C groups and a combined group of all typically reading participants showed a significant main effect for reading group, $F(2, 58) = 7.33$, $p = .001$. The D group scored significantly lower than the C group on phonological pretest primacy, $p = .023$, and posttest primacy, $p = .001$, by post hoc Tukey analysis.

Phonological primacy scores were significantly higher on the posttest than the pretest for all comparisons. Most typical and compensated readers received their highest mean scores for items at the beginning of the lists. In a comparison of D, C, and all typical reading groups, a repeated measures 3 × 2 ANOVA showed a significant phonological primacy score increase (i.e., significant main effect for test time) from pretest to posttest, $F(1, 58) = 28.26$, $p < .001$, ES = .33, with no significant interaction. Phonological middle position scores were also higher on the posttest than on the pretest, $F(1, 33) = 36.30$, $p < .001$. In this case, the interaction was significant. The pretest-to-posttest gain at this position was less for children with dyslexia than for the other groups, suggesting possible encoding or rehearsal deficits.

There was a reduced but still evident recency effect in the dyslexia group on the phonological posttest, in contrast to the phonological pretest. For the C group and the typical readers, there was no recency effect on the phonological posttest, although there was one on the pretest, $F(1, 58) = 22.86$, $p < .001$, with no significant Group × Position interaction.

Among typical readers, all phonological pretest serial position scores were significantly correlated with both word and pseudoword reading scores. Among D group readers, no significant correlations between phonological pretest serial position scores and reading scores were obtained.

Visual serial position curves are generally different in form from phonological curves (see Figure 5). They do not show a primacy effect (see Table 7), suggesting that visual cumulative rehearsal does not occur. Visual memory span primacy scores were significantly higher on the pretest than on the posttest for some of the group comparisons. Repeated measures ANOVA for the D group and its comparison groups showed a significant main effect for test time, $F(1,31) = 4.53$, $p = .041$. For the C group and its comparison groups, there was also a significant main effect of test time, $F(1, 53) = 4.80$, $p = .033$. Visual memory span recency scores were significantly lower on the posttest than on the pretest for C and its comparison groups, $F(1, 53) = 5.80$, $p = .02$, but not for D and its comparison groups.

The visual memory span posttest primacy score and posttest middle position score, representing visual recall of a newly learned visual character with visual retroactive interference, were significantly correlated with WRAT-3 word reading scores in typical readers, $r(27) = 48$, $p = .008$, and $r(27) = .44$, $p = .017$, respectively. The visual memory span posttest primacy score was also significantly correlated with word reading in the entire sample, $r(58) = .33$, $p = .010$. Visual memory span posttest middle position scores were significantly correlated with pseudoword reading in the children with typical reading skills, $r(27) = .41$, $p = .029$. None of the visual serial position scores were significantly correlated with reading scores in the D group.

# Discussion

## *Phonological Memory*

With respect to phonological memory, it was expected that in comparison to children with typical reading skills, children with dyslexia would have deficits in phonological memory for novel names. Reading ability–related differences in phonological memory were demonstrated in this study. Children with dyslexia showed deficits in phonological memory, as indicated by lower posttest scores and lower scores at all posttest serial positions than either comparison group. Significant associations between word and pseudoword reading scores and the phonological measures, especially phonological primacy, were obtained in the typically reading group. The only phonological score significantly associated with reading in the dyslexia group was the primacy score, possibly reflecting a deficit in phonological encoding or rehearsal that may limit reading ability in this group. Children whose dyslexia had been compensated did not have significantly lower mean scores at any of the phonological serial positions than the comparison groups.

Comparing the mean phonological pretest scores of children in the D group to those of their age- and reading-level–matched peers produced no significant differences. The lack of significant deficit in the D group on the phonological pretest requires some explanation, and perhaps it can be explained in the context of the theory of Baddeley and Hitch (1974). The range of phonological pretest scores was greater for children with dyslexia than for typical readers. Some of the highest phonological memory pretest scores obtained were among participants with dyslexia. Clearly, not all of the children in the D group had deficits in phonological memory span as measured by this test. If the children with dyslexia had phonological deficits, they must have had a means to compensate for them, which allowed some of them to do as well as the typical readers on the phonological pretest.

According to Baddeley's model of working memory (Baddeley, 1986; Gathercole & Baddeley, 1993), a two-part phonological loop supports memory for linguistic material. One part can employ subvocal articulation (phonological rehearsal) to support memory of verbal material (Baddeley, 1986). The other component is a passive phonological storage buffer, specialized for obligatory encoding of auditory–verbal input (Salame & Baddeley, 1982). Theoretically, the passive component is directly activated by auditory–verbal input, without the necessity of active rehearsal. If this buffer were functional in some readers with dyslexia, it might allow them to perform well on the pseudoword repetition task for short phonological strings (storage time is estimated at 1.5 seconds; Baddeley, Lewis, & Vallar, 1984) in spite of their phonological rehearsal deficits. Children with dyslexia who did well on the pretest pseudoword repetition test might be using this passive mechanism, reflecting recall without encoding and rehearsal. On the phonological posttest, the higher phonological encoding ability of typical readers apparently gave them an advantage that surpassed any gained by effective echoic memory in the D group.

If high phonological memory span performance in some children with dyslexia is based on articulatory storage without rehearsal, these children might be expected to show sharply diminished performance when the storage capacity of the buffer is exceeded. Among children in the D group, the three highest scorers on the phonological pretest were able to correctly reproduce most of the elements of the four-pseudoword lists but less than 45% of the phonological elements in the five-pseudoword lists. Two of these children were not willing to attempt the six-element lists, and one tried but did not correctly repeat any of the phonological elements. The three highest scoring typical readers, who received similar scores on the phonological pretest, tried the six-element lists, correctly repeating 85%, 41%, and 41% of the phonological elements on these lists (see Table 8).

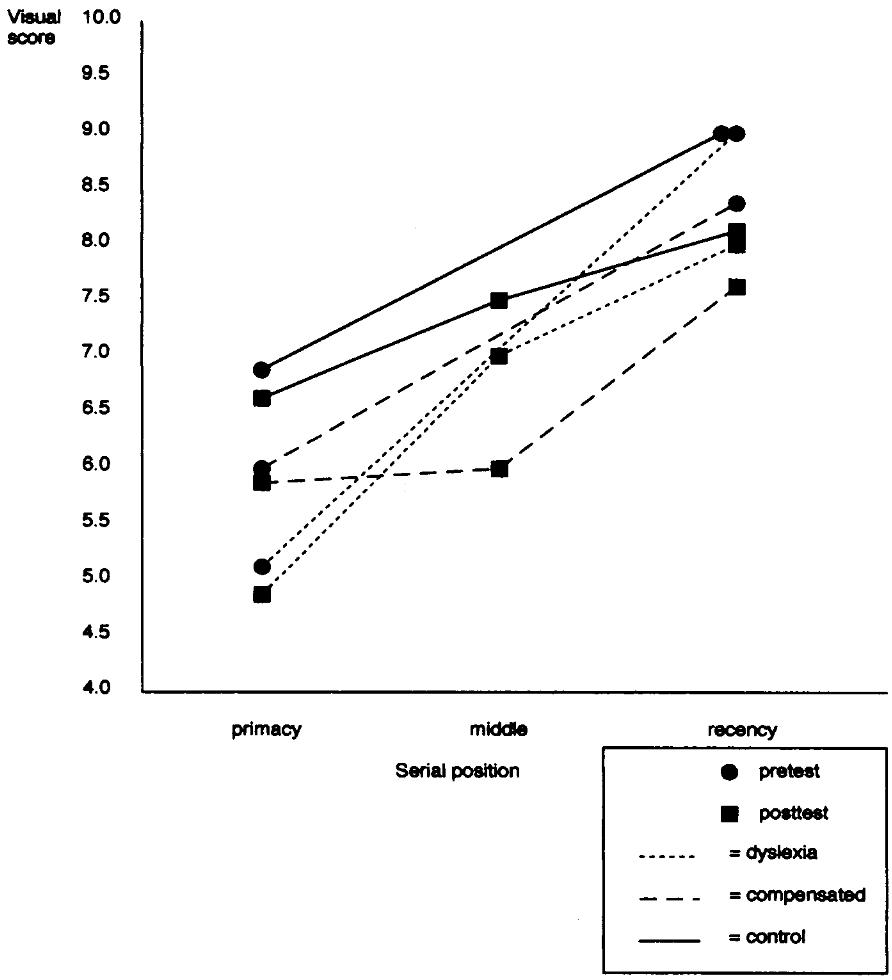


**FIGURE 5.** Visual memory span pretest and posttest serial position scores for all groups.

Developmental studies have shown that the ability to read tends to develop concurrently with the ability for phonological rehearsal (Walker, Hitch, Doyle, & Porter, 1994). Phonological primacy is taken to represent the role of phonological rehearsal in supporting memory for verbal material, which is essential for fluent reading (Baddeley, 1986; Baddeley & Hitch, 1974; Hulme & McKenzie, 1992; Spring & Capps, 1974). Individuals have the most time to rehearse the earliest list items, so they will remember them best. As young children are learning to read, their primacy performance should improve.

It was expected that phonological memory span scores would be positively related to reading scores. Significant relationships were obtained, especially in children with typical reading skills, between phonological primacy (as measured by primacy effects on the nonword repetition test) and reading scores. This provides support for the premise that phonological rehearsal ability is related to reading development. The lower scores on phonological pretest primacy obtained by younger beginning readers in the D-RL group reinforce this conclusion,

**TABLE 8**
Comparison of Phonological Pretest Scores for Highest Scorers Among Children with Dyslexia and Typical Readers by Number of Elements in List Recalled Correctly

| | D group participant | | | MC group participant | | |
|---|---|---|---|---|---|---|
| **Score** | **1** | **2** | **3** | **4** | **5** | **6** |
| Total | 126 | 122 | 90 | 123 | 122 | 111 |
| 3-element list | 38 | 36 | 35 | 37 | 38 | 35 |
| 4-element list | 50 | 49 | 39 | 47 | 44 | 39 |
| 5-element list | 30 | 26 | 28 | 55 | 39 | 26 |
| 6-element list | 0 | 0 | 0 | 58 | 28 | 28 |
| 7-element list | 0 | 0 | 0 | 11 | 0 | 0 |

*Note.* D = children with dyslexia; MC = controls matched on chronological age or reading level.

as these Grade 1 readers are at an age when rehearsal skills are thought to be developing (Hayes & Schulze, 1977; Hitch, Halliday, Schaafstal, & Heffernan, 1991; Hitch, Halliday, Schaafstal, & Schraagen, 1988; Walker et al., 1994). The laborious processing of text observed in beginning readers has been attributed to deficient rehearsal skill.

Phonological primacy scores were compared to phonological middle position scores to determine whether the primacy effects (higher score for beginning list items) were significant. There were no significant primacy effects for the phonological pretest in the D group, but pretest primacy effects were significant in all other groups. Phonological posttest primacy effects were significant in all groups. This suggests that phonological rehearsal may have been a memory strategy used only by typical readers and children in the C group on the phonological pretest, and by all participants on the phonological posttest.

Children with dyslexia may not have been able to use phonological rehearsal as an effective memory strategy on the phonological pretest due to encoding limitations for the novel sound combinations. They may have relied on echoic memory instead, at least for the shorter sequences. As the sounds became more familiar through the sound–symbol training, encoding them may have become easier for the children with dyslexia. On the phonological posttest, children with dyslexia showed reduced primacy effects relative to their matched peers, but the primacy effects were significant, suggesting that the children in this group can use phonological rehearsal to support memory of verbal material. This is consistent with the results of Gathercole and Baddeley (1990a). The limitations in phonological memory of the children in the dyslexia group may have been more related to the encoding of the novel sound combinations than to rehearsal ability.

Following the sound–symbol training procedure, memory span for the sounds was expected to increase in typical readers but not in children with dyslexia. The sound–symbol training did facilitate performance on the phonological task for typical readers as well as for children with a history of dyslexia. All groups had significantly higher phonological memory span scores on the posttest than on the pretest. Training interacted significantly with the phonological scores, resulting in significantly greater gains for typical readers than for participants in the D group and in significant differences in phonological posttest scores between children in the D group and their age-matched peers. The facilitative effect of the training was less pronounced in children with dyslexia than in typical readers. This may be because the children with dyslexia had more difficulty discriminating, encoding, or retrieving phonological elements from memory than their typically reading peers (Badian, 1998; Siegel & Linder, 1984; Siegel & Ryan, 1988), but it may also reflect a reduced benefit from having a visual symbol to associate with the sound. The increase in the scores from pretest to posttest may be due to increased familiarity with the sounds gained through the training (i.e., better phonological representations; Torgesen et al., 2001) and possibly also to the facilitative effect of multiple coding.

Children with dyslexia were expected to have deficits in memory span for newly learned sound–symbol associations in comparison with typical readers. Cross-modal memory scores, as represented by the sound–symbol training procedure used, were related to reading across all reading groups. This supports the findings of Snowling (1980) and others (Spector, 1995; Walton et al., 2001) that reading skill deficits of children with dyslexia are associated with extreme difficulties in learning to apply symbol–sound correspondence rules.

Training scores also showed significant group differences between the D group and both its matched comparison groups and between the C group and its age-matched comparison group. Fifty percent of the children with dyslexia, but only 7% of the typical readers, did not master the 10 sound–symbol associations during the sound–symbol training intervention. Mauer and Kamhi (1996) also found children with dyslexia to be slower to learn sound–symbol correspondences than typical readers in their study of memory for visually and phonologically similar and dissimilar correspondence pairs. This is in contrast to Swanson's (1986) report that there was no reading-related difference between groups in number of trials to criterion on his sound–symbol training procedures. However, Swanson used meaningful common words as names, and the present study used pseudowords. The pseudowords are novel sound combinations, so they were probably harder for the children to memorize than familiar combinations. Clearly, this was especially true for children with dyslexia.

It was expected that if associative memory deficits in readers with dyslexia are a product of phonological deficits, phonological memory span would be positively correlated with memory span for newly learned sound–symbol correspondences in the D group. Training scores were significantly related to phonological serial position scores in the Grade 1 readers of the D-RL group. The training scores were significantly correlated with iconic memory scores in typical readers. Training scores were *not* significantly associated with any of the memory variables in the dyslexia group. Cross-modal deficits among children with dyslexia are significant and seem to be somewhat separate from visual and phonological skills as represented by the tests used in this study. This suggests that deficits in sound–symbol association memory in the children with dyslexia are not a simple product of phonological and visual deficits but may be a separate area of impairment. Cross-modal deficits in the D group do not seem to merely reflect deficits in the phonological aspects of the task, as has been suggested by other researchers (McDougall et al., 1994; Vellutino & Scanlon, 1982).

Developmental studies of memory have indicated that young children and beginning readers rely on visual memory more than on verbal memory in image recall (Hitch, Halliday, Dodd, & Littler, 1989; Hitch et al., 1991; Hitch, Woodin, & Baker, 1989; Mann & Liberman, 1984; Paivio, 1986; Stanovich, 1986; Walker et al., 1994). Lack of spontaneous use of a phonological rehearsal strategy is assumed to be a major reason for the reliance on visual memory observed in younger children (Hayes & Schulze, 1977; Hitch et al., 1991; Hitch et al., 1988; Walker et al., 1994). This may also be true for children with dyslexia. Reading skills and rehearsal capabilities seem to develop concurrently, so that in the elementary years children rely on verbal rather than on visual memory to support the recognition of letters (Walker et al., 1994) and words (Stanovich, 1986). Stanovich (1986) suggested that as reading becomes more skilled, visual–orthographic strategies again predominate, except for some unfamiliar words.

In this study, cross-modal performance seems to depend on phonological skills in very young children. Among the Grade 1 students participating in the study (the D-RL group), only phonological pretest primacy scores (reflecting the rehearsal of novel sound combinations) were significantly associated with word and pseudoword reading ability. When the older typical readers are included in the correlation, significant associations of reading and other memory measures, especially iconic memory, emerge. Sound–symbol training performance seems to become more dependent on visual skills as children get older.

Stanovich (1986) defined skills that are developmentally limited with respect to their effect on reading. That is, some skills affect the acquisition of reading at certain stages but become so automatic at later stages that they no longer are limiting factors. Phonological encoding may reflect a skill that is usually involved in the learning of sound–symbol correspondences in a developmentally limited way. Most of the typical readers tested in this study were probably able to encode the novel sound combinations sufficiently easily that learning the pseudowords themselves was not a limitation for them in learning the sound–symbol associations. Developmentally persistent phonological encoding limitations may affect the ability of children with dyslexia to learn novel sound–symbol associations.

If the tendency to use verbal labels to support visual memory develops concurrently with beginning reading skills (Hitch et al., 1988; Hitch et al., 1989; Hitch et al., 1991; Walker et al., 1994) and its development is essential for cross-modal performance, training and phonological scores should be positively associated in the children in the D-RL group. A significant association of phonological posttest serial position scores and training scores was observed in these beginning readers.

Another hypothesis examined was that in comparison to children with typical reading skills, children with dyslexia would show lower recall of items at the beginning of phonological sequences but similar recall of items at the end of sequences. The phonological pretest curves for the D group most closely resemble those for the reading level control group children. The phonological pretest results suggest that phonological memory in the group with dyslexia is comparable to that of younger children reading at the same level. Based on this finding, one could conclude that the relationship of phonological memory to reading in children with dyslexia can be characterized as a developmental delay (Baddeley, Ellis, Miles, & Lewis, 1982; Bryant & Impey, 1986).

The phonological pre- and posttests are both tests of phonological memory. The pretest is a measure of memory span for novel stimuli, and the posttest measures memory for familiar stimuli. Dyslexia and reading level–matched groups scored similarly with novel phonological stimuli, but significantly differently with the learned stimuli. The D-RL group gained most following the training, and the D group gained least. The effect of sound–symbol training on phonological posttest scores refutes the assumption that phonological memory in the D group is similar to that in the D-RL group. Phonological memory in the D group was much less facilitated by the training, suggesting that the D group children did not remember the pseudowords as well as the D-RL children.

Unlike the D group, D-RL group children did show significant primacy effects in phonological memory, even on the pretest, so apparently they were able to encode and rehearse the novel sound combinations. If children need to develop phonological encoding skill to a certain level before they can gain knowledge of sound–symbol correspondences, this must happen before Grade 1, as the encoding per se does not appear to be a limitation for the D-RL children. Lower phonological pretest scores in this group than among older typical readers may reflect a limitation in the ability to rehearse longer series of the sound combinations, consistent with the results of Walker et al. (1994). Although the phonological pretest performances of the children with dyslexia and their reading level–matched peers were similar, the performances seemed to reflect different types of limitations. The children in the D group seem to be limited by encoding ability, as reflected by the lack of pretest primacy.

Perhaps the young children in the D-RL group are particularly adept in mastering novel sound combinations. This seems logical, as Grade 1 children are at a stage when their vocabulary is likely to be growing fast. The difference between the children with dyslexia and their reading level–matched peers in their response to the training intervention suggests a developmental deviance in the children with dyslexia as opposed to a developmental lag. This supports the findings of O'Shaughnessy and Swanson (1998) and others.

Phonological posttest serial position scores did not show recency effects (i.e., a significantly higher score at the recency position relative to the middle position score), as did the pretest scores in the typically reading and C groups (see Figure 4). Primacy and middle position scores were significantly higher on the phonological posttest than on the pretest for typical readers and children whose dyslexia had been compensated, indicating more effective rehearsal of posttest lists. The increase in primacy scores and the reduction in recency effects following training suggests that the children were using phonological rehearsal to support memory but that by doing so they impaired their ability to recall the most recent stimuli.

The performance of participants with dyslexia on the phonological posttest was lower than that of comparison groups, and their mean phonological posttest recency was lower than their pretest recency. Still, significant recency effects were present on the posttest in this group. The children in the D group showed a strength in phonological recency relative to their overall performance, suggesting strategic differences. Strength in phonological recency in readers with dyslexia has also been demonstrated in other studies (Farnham-Diggory & Gregg, 1975; Spring & Capps, 1974).

Coltheart (1980) described a processing bottleneck in memory as follows:

> Setting up an iconic memory consists of temporarily attaching various forms of physical information to a permanently existing entry in the internal lexicon. The attachment is a rapid, automatic process of unlimited capacity; but the attached information decays rapidly . . . . A lexical monitor must operate on the physical information, transforming it into some more durable form. (p. 223)

Coltheart suggested that the lexical monitor has a limited capacity, which may vary among individuals. The effort to stabilize the phonological contents of the passive storage buffer (hypothesized by Baddeley, 1986) by phonological rehearsal may be a processing bottleneck for children with low phonological skills.

## Visual Memory

In addition to phonological difficulties, children with dyslexia may also have deficits in visual memory for pseudoletter forms (Badcock & Lovegrove, 1981; Eden et al., 1995; Lovegrove & Brown, 1978; Lovegrove, Billing, & Slaghuis, 1978; Lovegrove, Heddle, & Slaghuis, 1980). Although many authors have claimed that visual coding is intact in children with dyslexia (Hulme, 1988; Katz et al., 1981; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979; Torgesen, 1988; Vellutino et al., 1975; Vellutino, Steger, & Kandel, 1972), the children in the D group showed a significant deficit relative to age-matched comparison students on the iconic memory pretest. In fact, relative to both its comparison groups, the D group had consistently lower scores for visual memory for pseudoletters. The possibility of a strength in iconic memory storage among children with dyslexia was not supported in this investigation. The children with dyslexia had deficits in visual iconic memory relative to the age-matched group as well as to the reading level–matched group when age was used as a covariate.

It was expected that scores on visual iconic memory and visual memory span would be positively related to reading scores. Visual memory scores actually presented a more complex picture than phonological scores in their relationship to reading. Iconic memory was significantly higher in children in the C group than in children in the D group. When the data for D and C groups were combined, the iconic pretest score was significantly related to the WRAT-3 score, $r(28) = .46, p = .01$, and the WRMT-R score, $r(28) = .40, p = .03$, although this correlation was not significant in either of these groups separately or in the groups of typical readers. Iconic memory pretest scores were significantly correlated with word and pseudoword reading (using partial correlation, controlling for age), $r = .62, p = .001$, in the entire sample. This correlation may reflect the significant relationship between iconic memory and reading observed in the D and C groups but not among typical readers. The iconic memory measure, not obviously like a reading task, apparently tapped some cognitive skill important for reading, especially in children with dyslexia.

The association of iconic memory scores with both word and pseudoword reading in children with a history of reading disability may reflect either a strategic difference or a limiting role of the visual skill tapped in reading ability. The iconic memory test had a spatial requirement that was not present in the visual memory span test. This may be the factor underlying the observed association of iconic memory with reading, which seems unique to the children with a history of dyslexia. Previous research has provided evidence of spatial memory deficits in children with reading difficulties (Cornoldi et al., 1999; Enns et al., 1995).

Visual memory for pseudoletters, as measured by the iconic memory task, clearly plays a greater role in word reading than in pseudoword reading, as it is not significantly related to WRMT-R Word Attack scores in the total sample. This is logical, as visual memory for whole words plays an important role in fluent reading but could not play much of a role in the decoding of novel sound–symbol combinations. Stanovich (1986) noted that in typical readers, whole word reading occurs by an automatized visual route rather than by the more laborious process of letter-by-letter decoding. The correlation of iconic memory scores with word reading might reflect some aspect of the role that facility of, access to, and maintenance of visual representations play in the use of the visual route for word reading.

Visual memory span posttest scores were not significantly associated with either reading measure in any group, but some of the serial position scores were related to reading scores. Visual memory span posttest primacy scores were significantly related to word reading in the entire population, and the primacy scores were related to word reading but not to pseudoword reading in typical readers. Visual memory span posttest middle position scores were significantly associated with word and pseudoword reading in typical readers. In children with a history of dyslexia (i.e., the D and C groups combined), there was a significant association of visual memory span posttest primacy with pseudoword reading. Maintenance of pseudoletter images in the presence of retroactive interference is presumably a determinant factor in performance on temporal primacy and has a logical relationship to skilled reading.

### *Training Effects*

Teaching associations between names and symbols was expected to increase memory span scores for the symbols in typical readers but not in children with dyslexia. Sound–symbol training did not result in an improvement in visual memory for the visual symbols. Rather, it seemed to do the opposite, more for typical readers than for children with dyslexia. Possibly, the reduction in performance from pretest to posttest observed in typical readers and in children whose dyslexia had been compensated represents their ineffective efforts to use verbal coding as a memory aid on a predominantly visual task. Other research has provided examples of nonproductive efforts to use a phonological strategy for a task best performed visually (Brandimonte, Hitch, & Bishop, 1992a, 1992b; Schooler & Engstler-Schooler, 1990). Typical readers are assumed to be flexible in their choice of memory strategies, but verbal coding seems to predominate and is, at times, used even when it is not the most effective strategy for a memory task (Brandimonte, Hitch, & Bishop, 1992c; Schooler & Engstler-Schooler, 1990). "It seems that, whenever possible, verbal recoding of visual stimuli is used, and this affects subsequent visual image processing" (Brandimonte et al., 1992a, p. 165). Readers with dyslexia are believed to have less flexibility in their choice of strategy (Swanson, 1986).

On the basis of a series of label training experiments, Swanson (1986) claimed that children with dyslexia are unable to combine verbal and visual codes additively. The results of this study may support Swanson's claim, but with some important differences. In Swanson's studies, children learned six real word names for filled geometric shapes. There was no reading-related difference in trials to criterion. The names used by Swanson were words that the children with dyslexia knew well. In the present study, the names were pseudowords, and although the shapes were more like letters, half of the children with dyslexia never reached the mastery criterion of being able to recite all names in one complete presentation of the set.

The sound–symbol training was expected to differentially affect visual memory span serial position scores in children with dyslexia and typical readers, producing a greater advantage in the children with typical reading skills. The training did differentially affect children with dyslexia and typical readers, but not in the direction postulated. In Swanson's (1986) study, name training reduced recall for children with dyslexia but increased it for typical readers. In this study, name training reduced visual recency scores for typical readers and both recency and middle position scores for C group children but not for the D group. Although this seems to contradict Swanson's results, it is not necessarily inconsistent with Swanson's conclusions. In Swanson's experiments, the typical readers mastered the codes and used them successfully to support recall. In this study, the verbal aspect of the sound–symbol task was more difficult. Typical readers may have had difficulty in using the sound–symbol associations to support visual memory span, and the effort to do so may have resulted in a decrement in recall. This is similar to what happened to the participants with dyslexia in Swanson's experiment. In this study, name training probably had less effect on recall for children in the dyslexia group because the children in this group did not appear to be using the names to support recall.

Swanson (1986) concluded that label training increases memory for visual forms in typical readers but seems to reduce visual memory in children with dyslexia. Phonetic reading methodologies, such as the Orton-Gillingham method (Gillingham & Stillman, 1987), the Spalding method (Spalding & Spalding, 1990), and the Slingerland method (Slingerland, 1971), have been used to teach reading to children with dyslexia. Phonics training is similar to the label training used by Swanson (1986), in that children are taught to form a verbal association with a visual image by simultaneous exposure to both the verbal and visual forms. These remedial methods are *multisensory* in the sense that

> our technique is based upon the close association of visual, auditory and kinesthetic elements. . . . Each new phonogram is taught by . . . processes, which . . . involve the association between visual (V), auditory (A) and kinesthetic (K) records to the brain. (Gillingham & Stillman, 1956, p. 40)

Spalding and Spalding (1990) stated that "if a child's aural, or . . . visual, recall of letters is weak and vacillating, then the other three avenues to the mind reinforce it and strengthen it" (p. 28). If children with dyslexia do not derive a memory benefit from using multiple codes, perhaps multisensory phonics instruction only confuses them and interferes with their reading skill development. Specific associative memory deficits among children with dyslexia may cause label training procedures such as phonics instruction to *reduce* their memory for visual stimuli (e.g., written words). The validity of phonics training as a remedial approach would then be questionable. In this study, children in the dyslexia group did show an increase in phonological memory span following the sound–symbol training, with no significant reduction in visual memory span for pseudoletters. So their decoding skills increased with no significant reduction in visual memory as tested.

Obviously, the novel sound–symbol relationships presented in this study were not overlearned to the point of mastery, and if they had been, a different pattern of results might have emerged (Fischer, 1993). But in this case, visual memory (essential to word reading) was reduced after sound–symbol training, and reduced more for typical readers than for children with dyslexia. The visual–phonetic associations presented in a multisensory program will not, by analogy, improve visual recognition of words if the sounds and associations are not mastered to automaticity. In fact, they may interfere with whole word learning. This is consistent with the conclusions of Meyer, Wood, Hart, and Felton (1998). Reduced fluency as a result of overreliance on a phonetic strategy could be less of a problem for children with dyslexia than for typical readers, possibly because readers with dyslexia will not try to use a phonetic strategy as diligently.

The phonological deficits observed in the children with dyslexia in this study seem best characterized as encoding deficits. These children may have difficulty in mastering sound–symbol correspondences because they have difficulty in becoming familiar with the sounds. The extensive repetition and drill of the sounds provided by a remedial phonics program is probably helpful in making the students with dyslexia more aware of the component sounds of speech (Torgesen et al., 2001). If encoding of sounds and sound combinations is the limiting factor, drill and repetition would support fluency and automaticity.

Clearly, the use of verbal labels for visual symbols can reduce visual response accuracy. This has implications for remediation, because in phonics training children learn to use sound–symbol associations to read by decoding. This may increase their reading ability to something approaching fluency, but it may also reduce automaticity to the detriment of comprehension (Stanovich, 1986). It would seem important, once children have learned to read by decoding, to emphasize sight reading of more common words and speed reading in general in order to avoid a reduction in fluency due to too much decoding. The need to develop a methodology to increase whole word reading in support of remedial phonics instruction has been emphasized (Badian, 1998; Felton & Pepper, 1995). The results of this study reinforce this conclusion.

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## AUTHORS' NOTES

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