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Dyslexia and Visual-Spatial Talents: Compensation vs Deficit Model

Ellen Winner

Boston College and Harvard Project Zero

Catya von Karolyi and Daphna Malinsky[1]

Boston College

Lisa French

Harvard Graduate School of Education

Colleen Seliger

Boston Veterans Administration Hospital

Erin Ross

Eunice Kennedy Shriver Institute

and

Christina Weber

Boston College

There are both theoretical and empirical reasons to support the hypothesis that dyslexia is associated with enhancement of right-hemisphere, visual-spatial skills. However, the neurological evidence is neutral with respect to whether dyslexic visual-spatial abilities should be superior (a compensation model) or inferior (a deficit model). In three studies we tested the hypothesis that dyslexia is associated with superior visual-spatial skills. Individuals with dyslexia not only failed to show superiority on a range of visual-spatial tasks, even when tasks were presented without time constraints, but also demonstrated a deficit on many tasks. Whereas we found attentional problems associated with dyslexia, these did not explain our findings. Results

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Address correspondence and reprint requests to Ellen Winner, Department of Psychology, Boston College, Chestnut Hill, MA 02467. E-mail: ellen.winner@bc.edu.

[1] Order of second and third author was determined by a coin toss. Both authors contributed equally to these studies.

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are discussed in terms of the apparent conflict between the failure to find any visual-spatial talent associated with dyslexia and the fact that dyslexia is overrepresented in certain visual-spatial professions.

Most research on dyslexia has attempted to determine the behavioral and neurological deficits at the core of this syndrome. Some researchers, however, have sought to demonstrate possible compensatory strengths associated with dyslexia. For instance, Orton (1925) suggested that dyslexia may sometimes be accompanied by spatial talents (see also Rawson, 1968). Similarly, Geschwind and Galaburda (1987, pp. 65–66) noted a high incidence of individuals with dyslexia in professions requiring spatial abilities, such as art, engineering, or architecture (Geschwind, 1982, pp. 22–23; Geschwind & Galaburda, 1987, pp. 65–66). And there is a growing popular view that dyslexia is associated with compensatory talents in the visual-spatial arena that allow individuals with dyslexia to excel in professions that capitalize on such strengths (e.g., computer graphics) (West, 1997).

Several case studies have described individuals with indisputable spatial talents who may also have been dyslexic (Aaron & Guillemard, 1993; Aaron, Phillips, & Larsen, 1988; Gordon, 1983; West, 1997). Individuals with both spatial talents and possible dyslexia include Edison, Leonardo da Vinci, Rodin, Faraday, Maxwell, and perhaps even Einstein, although there is considerable disagreement about Einstein (Holton, personal communication, 1998). Retrospective studies, however, are not strong evidence for such an association. First of all, they rely on guesswork rather than clinical diagnosis. In addition, retrospective studies on this topic are subject to hypothesis confirmation bias: Researchers study spatial individuals with dyslexia but neglect to note the incidence of spatial individuals without dyslexia or nonspatial individuals with dyslexia (cf. von Károlyi, 1998).

A few studies of spatial professions have demonstrated a disproportionate incidence of dyslexia in such groups. For example, art students reported more reading problems than did students in other areas, and they made more spelling errors, and more nonphonetically based spelling errors, than did students in other areas (Winner & Casey, 1993; Winner, Casey, DaSilva, & Hayes, 1991). These differences between art and nonart students remained even after scholastic aptitude differences were controlled. And a majority of students enrolled in a London art school reported difficulties with writing (Steffert, 1998). Artists also score poorly on measures of verbal fluency (Hassler, 1990).

Similar evidence has been found in fields of math and science, fields, which, like art, require spatial ability (Gardner, 1983; Krutetskii, 1976). Male math and science college majors were found to have more difficulties reading and spelling than students in other more verbal academic majors (Martino & Winner, 1995). Six of the 20 world-class mathematicians studied by Bloom (1985) reported some difficulties learning to read, and none of the 20 learned to read before school, despite their undoubtedly high IQs. All 34 of the inventors studied by Colangelo, Assouline, Kerr, Huesman, and Johnson (1993) reported difficulties in writing and in verbal areas, along with strengths in mathematics. And late-talking children have been shown to have a high proportion of relatives in spatial occupations (Sowell, 1997). While late talking is not a sign of dyslexia, and self-reported difficulties in reading, spelling, or writing may also not indicate dyslexia, these pieces of evidence are relevant to the claim that a language-based deficit may be associated with a compensatory spatial talent.

Thus, there is some evidence that individuals with spatial talents have a higher than average incidence of reading or language difficulty. What about the reverse: Do individuals with dyslexia have a higher than average incidence of spatial talents? Here the evidence is mixed.

If we ask only about relative spatial versus verbal abilities in dyslexic individuals, the findings are consistent. Not surprisingly, individuals with reading disorders perform better on spatial than on sequential or verbal tasks (e.g., Bannatyne, 1971; Gordon, 1983; Naidoo, 1972; Rugel, 1974; for a complete review of this literature, see von Károlyi, 1998). Thus, they have clear *relative* strengths in the spatial area. Bannatyne (1971) argued from this finding that individuals with dyslexia gravitate to occupations requiring three-dimensional, spatial thinking because they have a visual spatial orientation and a preference for thinking in three dimensions.

If we ask about absolute spatial strengths in individuals with dyslexia, there is some positive evidence, but the evidence is not consistent. In case studies of the brains at autopsy of four dyslexic males, Galaburda, Sherman, Rosen, Aboitiz, and Geschwind (1985) reported that one of the four individuals autopsied had been an engineer, one a sheet metal sculptor, and one was athletically gifted. Thus, three of these four individuals probably had higher than average spatial ability. Dyslexics were shown to be superior at rapidly discriminating between drawings of impossible versus possible figures, a task that requires integration of parts of a figure (von Károlyi, in press). Disabled readers were found to be superior in visual memory (Swanson, 1984). Art students with dyslexia performed better on a mental rotation task than did art students without dyslexia (Steffert, 1998). And across 11 studies, individuals with reading disorders outperformed control groups on the three spatial subtests of the WISC—Picture Completion, Object Assembly, and Block Design (Rugel, 1974). This is consistent with Bannatyne (1971), who found that two dyslexic subgroups had scores on Block Design that were significantly higher than average, and one had higher than average Object Assembly scores (cf. von Károlyi, 1988).

In some of the studies reviewed by Rugel (1974), however, the mean scaled WISC subtest scores of the disabled readers were no higher than WISC norms (von Károlyi, 1998). Relative but not absolute superiority on the WISC-R Performance Scale was also reported by Smith, Coleman, Dokecki, and Davis (1977) for children classified simply as ‘‘learning disabled.’’ While we cannot know what type of learning disabilities these children actually had, it is likely that many were dyslexic since dyslexia is the most prevalent form of diagnosed learning disability (Springer & Deutch, 1997). Other studies have also shown that individuals with dyslexia have spatial skills that are neither inferior nor superior to those of the population at large (Koenig, Kosslyn, & Wolff, 1991; LaFrance, 1997; Rourke & Finlayson, 1978; Rudel & Denckla, 1976; Siegel & Ryan, 1989).

In addition, to make matters even more complicated, Morris et al. (1998) found one subgroup of dyslexic (which he called the ‘‘Phonology-Verbal Short Term Memory Spatial’’ group) to be relatively weak in visual spatial abilities. However, it is not clear whether this group performed below average or simply below the relatively high performance of the control group (von Károlyi, 1998). Benton (1984) asserted that there is no evidence of an association of visual deficiency with dyslexia.

Thus, there is a modicum of evidence that dyslexics as a group have higher than average spatial abilities, but this evidence conflicts with other evidence that dyslexics have only average spatial ability. However, the disproportionate incidence of individuals with dyslexia in spatial fields cannot be ignored. The possibility that visual spatial talents accompany dyslexia requires further investigation.

What neurological model might lead us to predict an association between dyslexia and visual spatial talents and hence account for the disproportionate incidence of individuals with dyslexia in spatial fields? Geschwind (1984) proposed the concept of *pathology of superiority* to describe such a co-occurrence. Geschwind and Galaburda (1987) went on to account for such a co-occurrence in terms of the *Testosterone Hypothesis.* They suggested that exposure to (or atypical sensitivity to) testosterone *in utero* could lead to left-hemisphere language-related deficits and resultant compensatory growth in analogous regions of the right hemisphere. This was argued to lead to brains that were symmetrical (rather than the usual pattern of a larger left hemisphere). This set of events could then manifest itself as dyslexia accompanied by spatial talents (since the right hemisphere mediates many spatial abilities). The Testosterone Hypothesis was also argued to result in a tendency toward non-right-handedness and autoimmune disorders and allergies (Geschwind & Behan, 1982). Geschwind and Galaburda (1987) hypothesized that some of these talents, and/or some of these deficits, might also be found in the relatives of individuals with such a *pathology of superiority.*

There is empirical evidence for Geschwind and Galaburda's (1987) prediction of greater symmetry in dyslexic brains: all seven of the dyslexic brains studied at autopsy by Galaburda and his colleagues showed symmetrical temporal plana (Galaburda et al., 1985; Humphreys, Kaufmann, & Galaburda, 1990). However, the original claim was that symmetrical brains would result from inhibited left-hemisphere growth along with enhanced right-hemisphere growth (Geschwind & Galaburda, 1987). Autopsied dyslexic brains show that the symmetry is not due to a smaller left hemisphere, but rather to a larger right hemisphere, likely due to incomplete neuronal pruning (Galaburda, 1988; Galaburda et al., 1985, 1987, 1986; see Beaton, 1997, for a critical review of the evidence). It is known that symmetrical cortical areas are associated with atypical connectivity between hemispheres (Rosen, Sherman, & Galaburda, 1989). Humphreys, Kaufmann, and Galaburda (1990) speculate that the altered neuronal circuitry of symmetrical brains could result in altered cognitive capacities (whether superior or inferior is not specified).

The brains of dyslexics were also found to have microscopic cortical abnormalities of two types: architectonic dysplasias (excessive folding, fused laminae, and absent columnar organization) and neuronal ectopias (nests of neurons located in layer I, which is normally free of neurons) (Galaburda et al., 1985; Humphreys, Kaufmann, & Galaburda, 1990). These abnormalities were present on both sides of the brain. However, in the four male brains studied, the abnormalities were more prominent in the left hemisphere; in one of the three female dyslexic brains studied, the abnormalities were bilateral (Case 2), and in one, the abnormalities were more prominent on the right (Case 3) (Humphreys, Kaufmann, & Galaburda, 1990). (Two of the three female brains also had *glial scarring*, that is, zones without neurons.) Galaburda et al. (1985) argue that the brain lesions observed in these brains were acquired during the middle of gestation (during the time when neurons migrate to the cortex) and that such lesions lead to cerebral reorganization in the form of atypical growth and connectivity in the cortex.

Galaburda et al. (1985) speculate that the atypical findings in dyslexic brains could lead not only to dyslexia but also to the enhancement of other cognitive functions. They note that such a hypothesis is consistent with findings that cells compete for available synapses during development. Hence, lesions that inhibit language-related structures could lead to compensatory development of other structures. Since ectopias disrupt cortical development and lead to reorganization of neural pathways, the long-term developmental effects of ectopias could, in principle, result in enhancement of certain skills (Boehm, Sherman, Rosen, Galaburda, & Denenberg, 1996).

Studies of behavioral characteristics of mice with neuronal ectopias provide some support for the hypothesis that such lesions can lead to enhancement of certain functions, in this case, spatial ones. Mice with such ectopias have been shown to perform at a superior level on the Morris maze task, a spatial reference memory task in which one must remember a location that remains fixed across problems (Boehm et al., 1996; Waters, Sherman, Galaburda, & Denenberg, 1997). In contrast, ectopic mice performed worse than nonectopic mice on tasks that require working memory for information that changes from problem to problem. Given that ectopic mice show enhanced spatial reference memory, it is conceivable that human neuronal ectopias might also lead to enhanced spatial ability.

While it is possible that the kind of atypical brain development seen in dyslexia could result in enhancement of certain cognitive abilities, it seems equally likely that such atypical development could lead to deficits. In addition, the individual variability found in the brains of dyslexics studied at autopsy in terms of the quantity and location of cortical abnormalities suggests that there are likely to be considerable and unpredictable individual differences in the cognitive skills of dyslexics.

In the three studies reported here, we attempted to look systematically at possible spatial enhancement among individuals with dyslexia. We included sex as a factor because of the possibility that cortical abnormalities in the female dyslexic brain are more bilaterally distributed than are those in the male dyslexic brain. Whether presence of right-hemisphere abnormalities might lead to enhancement of or deficits in right-hemisphere skills could not be predicted. Hence, we looked for differences in either direction between spatial skills of male and female dyslexics.

STUDY 1

Method

Participants

A total of 60 young adults were tested. Twenty-one had been diagnosed at some point in their lives as dyslexic (10 male, 11 female) and 39 had no previously diagnosed reading disorders (16 male, 23 female). Dyslexic individuals were recruited in one of four ways. They were contacted after a screening of undergraduate psychology majors asking students to indicate whether they had ever been diagnosed with a reading problem; they were contacted by a mailing sent out to all students who had been seen at the campus tutoring center; they responded to flyers inviting students with reading problems to participate in a study examining ‘‘profiles of abilities’’ in students with reading problems (spatial abilities were not mentioned in the flyer in order to avoid a selection bias in terms of visual-spatial abilities); and three came to us by word-of-mouth when it became known that we were researching dyslexia. All were college undergraduates from the same institution with three exceptions: one had attended the same college but had dropped out a few years earlier and two were young adults working at the college but who had recently graduated elsewhere. Dyslexic students were paid $30 for their time. Nondyslexic students were psychology majors who participated as part of a requirement of the psychology major. All students were native English speakers. Because all but two of the participants attended or had attended the same undergraduate college, an SES difference between dyslexic versus nondyslexic students seems unlikely.

Materials and Procedure

Reading Measures

All participants were given two standardized reading tests. Students were first given all of the subtests of the Diagnostic Assessments of Reading (DAR) except for Word Analysis (which was thought to be too easy for students at the college level whose dyslexia was mild enough to have allowed them to get into a competitive college) (Roswell & Chall, 1992). The score received was the highest level at which the student demonstrated mastery, as defined by the DAR. The tests were begun at Level 6. Reading rate was then assessed by the Nelson–Denny Reading Test (Forms G&H) (Brown, Fishco, & Hanna, 1993), and raw scores were recorded.

Following the two reading tests, students were asked a set of questions about reading and reading-related abilities as well as one question about attention. They were asked whether they had had difficulty learning to read; whether they could read by the end of first grade, and if not, at what grade they could read; whether they read slowly; whether they had ever had a reading tutor; how often they read a book for pleasure; whether they had difficulty spelling, writing, or learning a foreign language in school; and

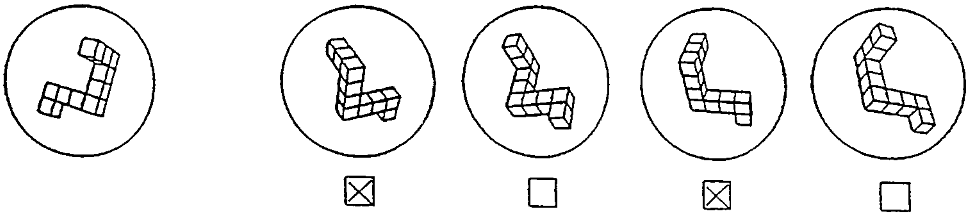

FIG. 1. Sample item, Vandenberg Test of Mental Rotation item, Studies 1–3. The task is to identify the two figures on the left that are rotated versions of the target. Correct choices are shown here.

whether they thought they had an attentional problem. This last question was an informal way of checking for attentional deficits that might interfere with task performance. Questions were posed orally, and the experimenter recorded responses.

Participants were then given three standardized spatial tasks, described below.[2]

Vandenberg Test of Mental Rotation

The Vandenberg Test of Mental Rotation, Version B (Vandenberg & Kuse, 1978) is a test of mental rotation ability. Each of the 20 items consists of a target figure, which is a line drawing of a three-dimensional complex figure, along with four choices (as shown in Fig. 1). Two of the choices are drawings of the same figure rotated into three-dimensional space. The other two choices are drawings of different but very similar figures. The task is to indicate which two of the four choices are identical to the target. For half of the items, the incorrect choices are drawings of figures which are mirror images of the target. For the other half, the incorrect choices are drawings of figures which have different features from the target. Participants are given 5 min for each of the two parts of this task.

This test was scored in the standard way. For each of the 20 items, a score of 2 was given if both answers were correct, a score of 1 if one answer was correct and the other left blank, and a score of 0 if one was correct and one wrong (to discount possible guessing responses), or if both answers were wrong or none attempted. The total possible score was thus 40.

Rey–Osterrieth Complex Figure Test

The Rey–Osterrieth Complex Figure is a test of perceptual organization and visual memory (Osterrieth, 1944; Rey, 1941). Participants are shown a line drawing of a complex figure (as shown in Fig. 2) and

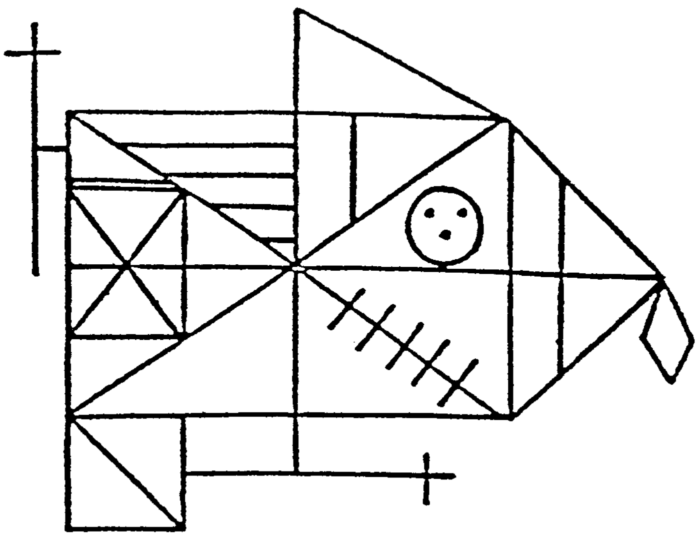

FIG. 2. Rey–Osterrieth Complex Figure, Study 1.

[2] Participants were also given a task requiring identification of impossible figures. This task was used in another, related study (von Károlyi, in press).

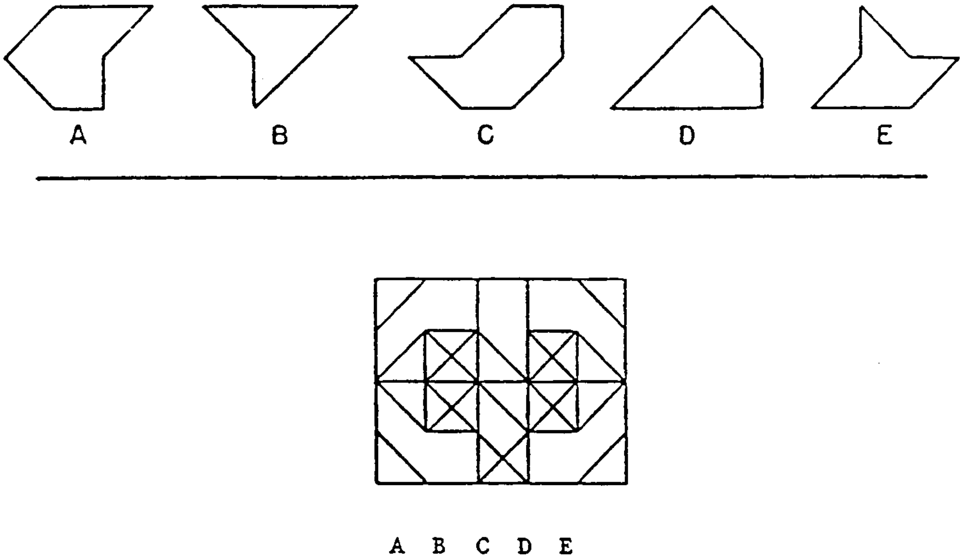

FIG. 3. Sample item Hidden Figures Test, Study 1. The task is to circle the letter under the complex shape to indicate which of the five simpler shapes is embedded in the complex shape (correct = B). Reprinted by permission of Educational Testing Service, the copyright owner.

are asked to copy the figure using a pencil and paper (Copy Condition). The target figure is then removed and participants are asked to reproduce the figure from memory (Immediate Recall Condition). Twenty minutes later, participants are asked to reproduce the figure from memory again (Delayed Recall Condition). No advance warning is given that the figure will have to be drawn from memory for either memory condition. In Study 1, only the Copy and Immediate Recall Conditions were administered.

Drawings were scored according to the developmental scoring system developed by Bernstein and Waber (1996). Two judges scored all of the data, and an interjudge reliability of 90% was reached. All disagreements were resolved by discussion.

Drawings of the target figure can be scored on a variety of dimensions (Bernstein & Waber, 1996). We assessed the drawings on three dimensions that assess the ability to recall and reproduce the overall organization and structure of the figure: level of Organization, incidence of Configurational Style, and level of Structural Accuracy. The Organization score assesses the ability to reproduce the ''organizational goodness'' of the figure (Bernstein & Waber, 1996, p. 2). The criterial features that make up the Organization score are the major structural units of the figure (e.g., base rectangle corners and base rectangle vertical and horizontal lines). Organization scores range from 1 to 13. The Style rating classifies the approach as Configurational, Part-Oriented, or Intermediate. To be credited with a Configurational style, one must draw the major structures of the figure (e.g., the base rectangle and its horizontal, vertical, and diagonal lines) with continuous strokes, and the relevant lines must be aligned properly. The Structural Accuracy score assesses the number of major structures (base rectangle and horizontal, vertical, and diagonal lines) that are reproduced and ranges from 0 to 25.

Hidden Figures Test

The Hidden Figures Test is a visual test of flexibility of closure (Ekstrom, French, Harman, with Dermen, 1976). The test involves searching a visual array in order to find one of five given target shapes. (A sample item is shown in Fig. 3.) To succeed, one must be able to hold a target shape in mind in order to disembed it from a more complex array. The task is difficult because one does not know which of the five shapes is the embedded one, so that each option must be tried until one is found embedded in the complex array. Only Part 1 of the test was administered (16 items), and participants were allowed 12 min for this task. The score was the number of correct choices and hence could range from 0 to 16.

Results

Reading Measures

A series of one-way ANOVAs by group (dyslexic vs nondyslexic) performed on each reading subtest confirmed that our dyslexic population was significantly im-

TABLE 1
Mean Scores and Standard Deviations on Reading Tests, Study 1

Test	Dyslexic *M* (*SD*)	Nondyslexic *M* (*SD*)
DAR Spelling	9.0 (3.0)	11.8 (0.7)
DAR Word Meaning	10.2 (2.6)	11.8 (0.9)
DAR Word Recognition	10.6 (2.9)	12.0 (0)
DAR Oral Reading	10.6 (2.6)	12.0 (0)
DAR Silent Reading	10.2 (3.0)	11.8 (0.6)
Nelson–Denny Reading Rate	187.3 (19.3)	213.5 (20.7)

Note. Higher scores indicated better performance.

paired in reading relative to our control group, as detailed below. Mean scores on each measure are reported in Table 1. A series of one-way chi-square tests (by Group) performed on the responses to the questions about reading-related difficulties also confirmed that the dyslexic group was impaired in reading relative to the control group, as detailed below. Table 2 summarizes the responses to these questions.

Diagnostic Assessment of Reading (DAR)

The dyslexic group performed significantly worse than the control group on all subtests of the DAR: Spelling, $F(1, 59) = 29.98$, $MS_e = 3.436$, $p = .0001$; Word Meaning, $F(1, 59) = 13.097$, $MS_e = 2.683$, $p = .0006$; Word Recognition, $F(1, 59)$, $MS_e = 2.813$, $p = .0026$; Oral Reading, $F(1, 59) = 26.031$, $MS_e = 2.258$, $p = .0012$; and Silent Reading, $F(1, 59) = 10.313$, $MS_e = 3.407$, $p = .0022$.

Nelson–Denny Reading Test

Dyslexics also had slower reading rates on the Nelson–Denny, $F(1, 59) = 22.883$, $MS_e = 410.523$, $p = .0001$.

Self-Report Reading Questionnaire

On all self-report measures, dyslexic participants indicated a higher rate of reading and reading-related difficulties, as shown in Table 2. More individuals in the dyslexic group had difficulty learning to read, $\chi^2(1) = 33.102$, $p = .0001$; did not read until

TABLE 2
Number and Percentage of Reported Self-Reported Reading-Related Difficulties, Study 1

Measure	Dyslexic *n* (%)	Nondyslexic *n* (%)
Difficulty learning to read	15 (71%)	1 (3%)
Reading only after 1st grade	8 (38%)	0
Had reading tutor	13 (62%)	1 (3%)
Read for pleasure once a year or less	10 (48%)	9 (23%)
Difficulty writing	11 (52%)	1 (3%)
Difficulty learning foreign language	12 (57%)	4 (10%)
Attentional problems	11 (73%)	4 (27%)

TABLE 3
Mean Scores and Standard Deviations on the Vandenberg Test of Mental Rotation, Study 1

	Dyslexic *M* (*SD*)	Nondyslexic *M* (*SD*)
Total score (of 40)		
Female	11.1 (6.5)	21.1 (8.2)
Male	23.3 (12.1)	26.3 (11.1)
Total	16.9 (11.2)	23.3 (9.7)
Total score/number attempted (of 2.0)		
Female	0.6 (0.4)	1.1 (0.5)
Male	1.2 (0.6)	1.5 (0.5)
Total	0.9 (0.6)	1.2 (0.5)

after 1st grade, $\chi^2(1) = 17.143$, $p = .0001$ (two reported learning to read only in 7th grade, and one not until the 6th grade); had a reading tutor, χ^2 $(1) = 26.869$, $p = .0001$; read for pleasure only once a year or less, $\chi^2(1) = 3.799$, $p = .0513$; had difficulty writing, $\chi^2(1) = 21.172$, $p = .0001$; had difficulty learning a foreign language, $\chi^2(1) = 15.345$, $p = .0001$; and reported more attentional problems, $\chi^2(1) = 14.657$, $p = .0001$. Responses to the questions about spelling and reading rate were not analyzed since we had standardized measures for both skills.

Visual Spatial Measures

A series of two-way, Group × Sex ANOVAs (or, where ANOVAs were not appropriate, one-way chi-squares, by group) were conducted on the spatial measures.

Vandenberg Test of Mental Rotation. As shown by ANOVA, and contrary to prediction, dyslexics performed significantly worse on the Vandenberg, $F(1, 56) = 6.329$, $MS_e = 90.662$, $p = .048$. Replicating previous findings showing a male advantage on this test (Linn & Petersen, 1985), females performed worse than males, $F(1, 56) = 11.237$, $MS_e = 90.662$, $p = .0014$, and this occurred irrespective of the presence or absence of dyslexia. Although the interaction between Group × Sex did not reach significance, $F(1, 56) = 1.835$, $MS_e = 90.662$, $p = .181$, Table 3 shows that dyslexic females performed strikingly worse than all other groups, achieving a mean score of only 11.1 of a possible 40. When females were dropped from the analysis and a one-way ANOVA was performed, the performance of the dyslexics was equivalent to that of the control group, $F(1, 25) = .423$, $MS_e = 131.897$, $p = .5214$.

To determine whether the low scores of the female dyslexic participants were due only to slower but not to less accurate performance, we calculated the number of correct items for each person divided by the number of items attempted. Because there were 20 items, each worth 2 points, the highest ratio one could achieve was 2.0. A person who attempted only 10 items but got them all right would thus attain the same ratio score as the person who attempted 20 and got them all right.

As shown in Table 3, the dyslexic group (males and females combined) also achieved lower scores on this measure. There was a main effect of group, dyslexics scoring worse, $F(1, 56) = 6.772$, $MS_e = .259$, $p = .0118$. And males outperformed females, $F(1, 56) = 13.898$, $MS_e = .259$, $p = .0005$. Inspection of the means showed that, again, the main effect of group appeared to be entirely due to the poor performance of the females. This was confirmed by an analysis without the females, showing that in a one-way ANOVA, the performance of the dyslexics was equivalent to that of the control group, $F(1, 25) = 1.04$, $MS_e = .337$, $p = .318$.

Thus, the poorer performance on the Vandenberg by the dyslexics was due to the female dyslexics only. And we were able to rule out the possibility that this poorer performance was due only to slower but not less accurate responding: Female dyslexic participants responded not only more slowly but also less accurately.

Rey–Osterrieth Complex Figure Test. As shown by ANOVA, and contrary to prediction, both groups performed equivalently to nondyslexics on the Organization measure in both the Copy and Immediate Recall Conditions of the Rey–Osterrieth. There was also no effect of sex.

As shown by a one-way chi-square test, and contrary to prediction, those in the dyslexic group were no more likely than those in the control group to copy or recall the figure using a Configurational style. Both groups performed equivalently.

Because almost all participants achieved perfect scores of 25 on structural accuracy in the Copy Condition, no analyses were performed. As shown by ANOVA, contrary to prediction, in the Immediate Recall Condition, dyslexics performed worse (X = 22.9, SD = 3.8) than nondyslexics (X = 24.5, SD = 1.4), $F(1, 56) = 5.551$, $MS_e = 6.062$, $p = .022$. Males outperformed females (Males: X = 24.5, SD = 1.0; Females: X = 23.6, SD = 3.3), and this effect neared significance, $F(1, 56) = 3.693$, $MS_e = 6.062$, $p = .0597$.

Again it was the female dyslexics who appeared to be carrying the main effect of group. When the analysis was repeated without the females, a one-way ANOVA revealed that the dyslexic group performed equivalently to the control group, $F(1, 25) = 2.095$, $MSe = 1.014$, $p = .1608$.

Hidden Figures Test. As shown by ANOVA, there was no difference between groups on the Hidden Figures Test, nor was there an effect of sex.

Discussion

Our analyses confirmed that, as predicted, individuals who reported having dyslexia performed significantly worse on all reading measures. Contrary to prediction, however, individuals with dyslexia either performed significantly worse than did the control group (females on the Vandenberg Test of Mental Rotation; males and females on the Rey–Osterrieth Structural Accuracy, Immediate Recall Condition) or they performed equivalently (Rey–Osterrieth Organization and Style, both conditions; Hidden Figures Test).

There are several possible explanations for our failure to demonstrate any spatial superiority among the dyslexic group. First, the dyslexic participants in Study 1 had all been admitted into a competitive undergraduate institution. Perhaps a compensatory spatial advantage manifests itself in proportion to the severity of dyslexia. Severely dyslexic individuals might be less likely to pursue admission to such an institution. In addition, many of our dyslexic students were majoring in psychology, which is not a spatially demanding major. Our dyslexic group may thus have represented a skewed sample of dyslexics (i.e., they may have been weaker in spatial skills than dyslexics selected at random). In order to be certain that our dyslexic population was not skewed, we carried out a second study in which we recruited the dyslexic group from a high school for individuals with language-based learning disabilities. Students at a school specially designed for students with learning disabilities are likely to have more severe levels of dyslexia than those who attend a regular college. Moreover, such students should not be skewed in any particular direction in terms of spatial ability.

A second possible explanation for our failure to demonstrate a spatial superiority in the dyslexia group was that our tasks were all standardized paper-and-pencil tasks. Perhaps these tasks do not reflect real-world spatial ability. Study 2 was also designed to test the hypothesis that on more real-world spatial tasks, dyslexics excel. Four new spatial tasks were introduced which we thought might better assess the kinds of spatial abilities used by individuals in spatial professions such as architecture, engineering, physics, and art: a three-dimensional puzzle task, a spatial visualization task in which one had to visualize the direction of the turn of a screw, a test of verbally presented problems with require spatial visualization for their solution, and a drawing task. In addition, we added one more standardized spatial test—a test in which one must complete a matrix by selecting the appropriate pattern.

A third possible explanation for our failure to demonstrate spatial superiority in the dyslexia group was that our tasks were all timed. Recall that there was a higher proportion of attentional problems reported by participants with dyslexia than by those without. Perhaps attentional difficulties place individuals at a disadvantage on timed tasks. In addition, dyslexics with or without attentional problems may simply have difficulty responding rapidly. This would be consistent with the findings of Johnston and Weismer (1983) that children with ‘‘language disorders’’ had longer latencies on a mental rotation task than did a control group, but were not less accurate. A difficulty in speed of processing both verbal and nonverbal tasks may be a characteristic of dyslexia (Wolf, Bowers, & Biddle, 2000). We tried to correct for this by assessing the ratio of number correct to number attempted on the Vandenberg, yet we still were not able to demonstrate a dyslexic advantage. However, perhaps simply knowing that one is taking a timed test is stressful, and perhaps this accounts for the poor performance of the dyslexic group. Thus, in Study 2, all of our tests were administered as untimed tasks.

We considered a possible explanation for our failure to demonstrate a dyslexic disadvantage on the Hidden Figures Task. This task proved extremely difficult for all participants, and therefore a floor effect might have masked underlying differences between groups. In Study 2, thus, we altered the Hidden Figures Task to make it easier.

STUDY 2

Method

Participants

A total of 37 students participated in Study 2. Fifteen had been diagnosed as dyslexic (9 male, 6 female) and 22 (8 male, 14 female) had no previous diagnosis. The dyslexic students were in grades 9–12 at a school for students with language-based learning disabilities. They were paid $30 as in Study 1. The nondyslexic students were college undergraduates ($n = 20$) or high school students ($n = 2$).

Materials and Procedure

Students were seen in one 2- to 3-h session, with a break provided. (Some dyslexic students took up to 3 h; others, and most of the students in the control group, took only 2 h.) Students received eight spatial tests along with several measures of reading ability. The spatial tests included the three from Study 1 (with modifications described below) and five new ones. All spatial tests were administered without time restriction.

Reading Measures

Woodcock Johnson. Participants were given the Woodcock Reading Mastery Test, Revised, Form G (Woodcock, 1987). Raw scores were recorded.

Nelson–Denny reading measures. Reading rate was assessed by the Nelson–Denny Reading Test (Forms G and H), and raw scores were recorded, as in Study 1.

Spelling measure. The spelling subtest of the Diagnostic Assessments of Reading (DAR) was administered (Roswell & Chall, 1992). The score received was the highest level at which mastery was achieved, as defined by the DAR.

Auditory Analysis Test. The Auditory Analysis Test (Rosner & Simon, 1970) was administered. In this test, participants hear a series of words which they must first pronounce as heard and then pronounce omitting part of the word (e.g., Say ''scold.'' Now say it again but without ''*sc*''). The score received was the total number of correct, and scores could range from 0 to 40.

Rapid naming rate measures. Four Rapid Automatized Naming (RAN) tests were administered (from Denckla & Rudel, 1974; object naming task revised by Wolf & Obregon, 1992, 1997), along with two Rapid Alternating Stimulus tests (RAS) (from Denckla & Rudel, 1976). The RAN tests were composed of 50 items each (five items repeated 10 times in random order). Participants were asked to read off the arrays from left to right as rapidly and as accurately as possible. The arrays consisted of five drawings of common objects (book, chair, dog, star, and hand), five high-frequency colors (red, yellow, green, blue, and black), five numbers (2, 4, 6, 7, 9), and five high-frequency lowercase letters (a, d, o, s, and p). The two-set RAS tests were composed of 50 items (five letters and five numbers) randomly intermixed. The three-set RAS tests were composed of 50 items (five letters, five numbers, and five colors) randomly intermixed. Time to read the items was recorded.

Spatial Measures

Vandenberg Test of Mental Rotation. As in Study 1, participants were given the Vandenberg Test of Mental Rotation, Version B (Vandenberg & Kuse, 1978). Only Part 1 (10 items) were given. The amount of time taken was recorded surreptitiously by stopwatch held in the experimenter's lap. Participants were not told that their time was being recorded. Thus we were able to analyze number of correct responses on an untimed task as well as the total amount of time taken to complete the task.

Rey–Osterrieth Complex Figure Test. As in Study 1, participants were given the Rey–Osterrieth Complex Figure Test. Two changes in the procedure used in Study 1 were introduced. First, as specified by the Bernstein and Waber (1996) method of administration, participants were asked to use five different colors of pens. Every 30 s, they were handed a new pen to use. Use of different colors makes it easier to determine whether participants are using one continuous line, a criterion which must be taken into account in scoring for Style. Second, in addition to the Copy and Immediate Recall conditions we added the Delayed Recall condition, in which participants were asked to draw the figure again after 20 min, without knowing ahead of time that they would be asked to do so. As in Study 1, two judges scored the drawings, and an interrater reliability rate of 90% was achieved.

Archimedes' Screw. Participants were given a task developed by us to assess spatial visualization in a way that we hoped would capture the kinds of spatial tasks in which an inventor or engineer might engage. Participants saw a series of pictures of Archimedes' Screw, a device invented by Archimedes to move water from a lower to a higher level. They were asked to decide which way the screw would have to turn in order to bring water up. To solve this task one must form a mental image of the screw, and one must then try out turning the screw in each of two directions, all the time visualizing which direction water inside the tube would move (up or down) given the turning of the screw. While this itself is not an ordinary task that people confront in the real world, the skills required seem to be the kinds of skills that an inventor would use in imaging how a new device would actually work.

First, participants saw a picture of Archimedes Screw [Fig. 4a (without the arrow)] along with the following explanation:

> This is a picture of a machine that can turn. This is water down here (E points). The picture gives you a cut out view of what is inside this tube (E points to cut out). The inner part that you see through the cut out goes from the top of the tube to the bottom.
>
> Function Question: What do you think this machine can do if you turn the handle at the top? (Correct response: machine brings water up.)

Next, they were shown two images of the same screw, each with an arrow indicating it was turning in a different direction (Figs. 4a and 4b), and were told that the arrows showed the way that the tube is turning.

> Turn Question #1: If you turn the tube one way, the water will go up. Show me the one where the water will go up. (Correct response: a)

Next they were shown the incorrectly drawn screw in Fig. 4c (without the arrows). Either the screw is turning clockwise and bringing the water up or the falling water is making the screw turn counterclockwise. We asked:

> Turn Question #2: The water falling from E to F to G is making the tube turn. Which way is the tube turning? Is it turning like this (Fig. 4c) or like this (Fig. 4d). (Correct response: c)
>
> Finally they were shown Figs. 4c and 4d (with arrows) and asked:

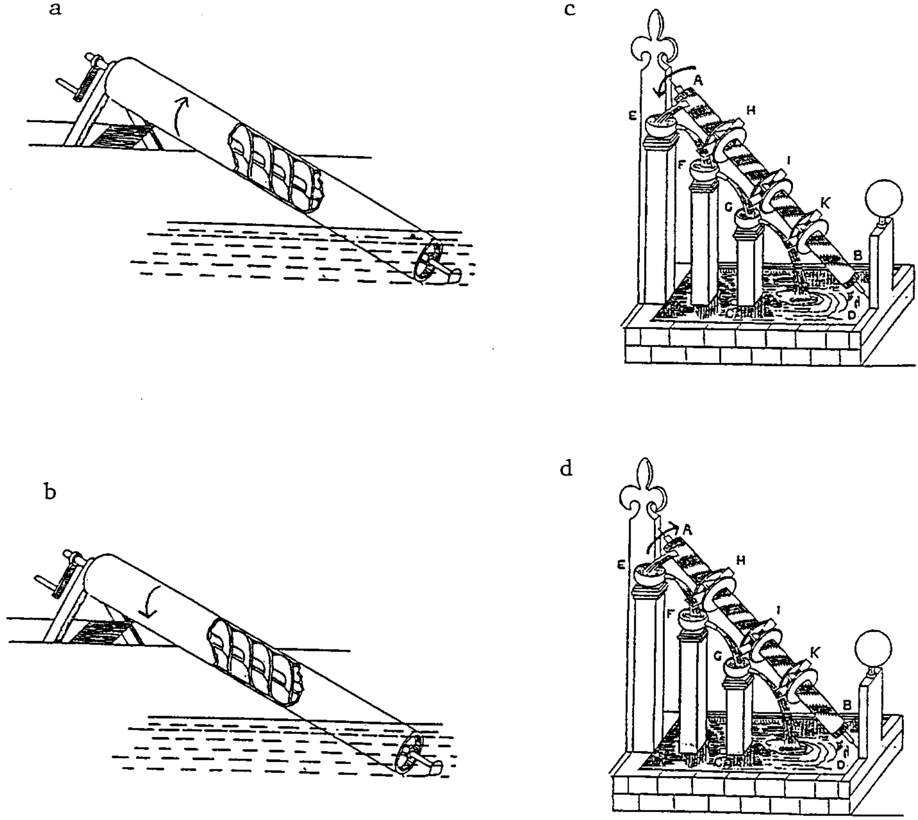

FIG. 4. Archimedes Screw images. (a) Correct turning direction to bring water up; (b) incorrect turning direction to bring water up; (c) impossible figure: turning direction would not bring water up, but falling water suggests that the screw is bringing water up; and (d) impossible figure: turning direction would bring water up, but falling water would turn the screw in the wrong direction for raising the water.

> Turn Question #3: If you turn the tube one way, the water will go up. Show me the one where the water will go up. The arrows show you the way the tube is turning. (Correct response: d)

We used the ''impossible'' depictions (Figs. 4c and 4d) to assess the recognition that while the screw is in fact turning counterclockwise (as shown by the falling water), the screw would have to turn clockwise to bring the water up. The final question was considered the most difficult. To get it correct, one must disregard the contradictory cue of the water falling (which would make the tube turn counterclockwise), and realize how the tube would have to turn to bring the water up (clockwise).

Pyramid puzzle. Participants were given a hands-on, non-paper-and-pencil puzzle to complete. They were asked to assemble four wooden blocks into a three-sided pyramid. This is a difficult task, and if after 2 min no solution had been found, a hint was provided: ''Here's a hint. Find the top of the pyramid, then figure out a way to support it.'' Participants were told they could have as much time as they needed. However, if after 5 min no solution had been found, we moved on to the next test. We recorded whether the puzzle was solved, the amount of time taken, and whether a hint was given before the solution.

Drawing task. Participants were given a sheet of paper and a sharp pencil and were asked to draw their own hand as accurately as possible. Drawings were classified independently by two judges as either showing some degree of talent, as average, or as primitive. See Fig. 5 for sample drawings.

Spatial word problems. Participants were given a series of 12 verbally presented problems used by Hermelin and O'Connor (1986), listed in Table 4. These problems must be solved through spatial visualization: one must construct a mental image and operate on it, e.g., ''A painted wooden cube with an edge of 9 cm. is cut up into little cubes each of a 3 cm. edge. There will be 27 of these little cubes. How many of them will have only two painted sides?'' The correct answer to this is 12, and a clear

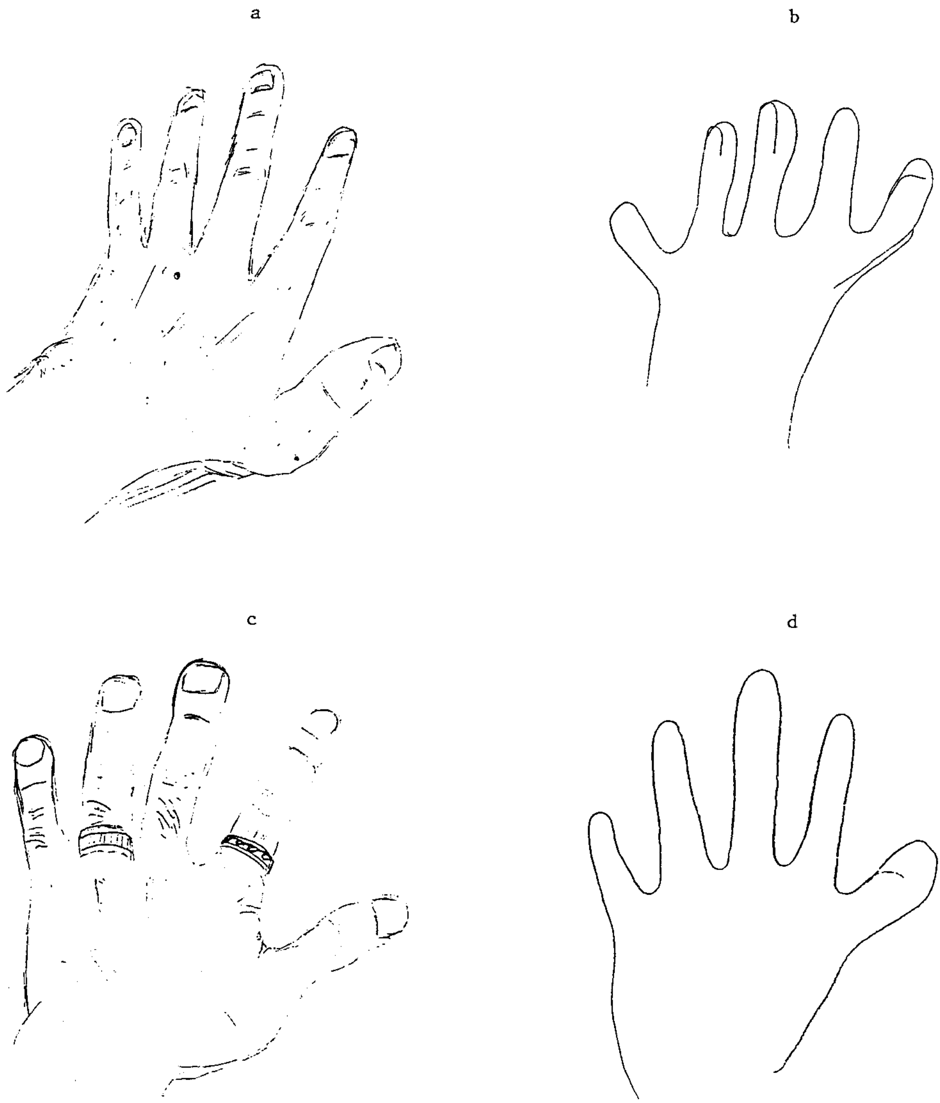

FIG. 5. Sample hand drawings. (a) talented, dyslexic; (b) primitive, dyslexic; (c) talented, nondyslexic; (d) primitive, nondyslexic.

way to solve this is to imagine the cube and count the number of smaller cubes which would only have two painted sides.

K-Bit Matrices. Participants were given matrices from the Kaufman Brief Intelligence Test (K-BIT) (Kaufman & Kaufman, 1990). (Participants were also given the verbal subtest of the K-BIT but performance on this subtest was not analyzed, as we realized such scores would be redundant with the many other verbal measures administered.)

Hidden Figures. As in Study 1, the Hidden Figures task was given, but in simplified form. While in Study 1 the test required participants to find one of five figures in a larger pattern, in Study 2 the test required finding only one given figure in a larger pattern (items 1–4) and then one of three given target shapes in a larger pattern (items 5–8). Scores could range from 0 to 8. (See Fig. 6 for a sample item.)

Measures were administered in the following order: Vandenberg, Archimedes, Pyramid, Hand Drawing, Hidden Figures, Rey–Osterrieth Copy and Immediate Recall, Spatial Word Problems, Questionnaires, K-BIT, Woodcock, Nelson–Denny, DAR, Auditory Analysis, and Rapid Auditory Naming. The Delayed Recall condition of the Rey was administered 20 min after the Rey Immediate Recall condition.

There were a few missing scores for some of the participants due to scheduling constraints which

TABLE 4
Verbally Presented Spatial Problems/Answers, Study 2
(from Hermelin & O'Connor, 1986)

1. How many diagonals are there on the surface of a cube? (12)
2. A painted wooden cube with an edge of 9 cm is cut up into little cubes each of a 3-cm edge. There will be 27 of these little cubes. How many of them will have only two painted sides? (12)
3. A pencil is fastened at one end and the other end is free to move in any direction in space. What shape will it describe? (arc, circle, flower)
4. The midpoints of each of the sides of a square are joined together by a line. What figure will result? (square, diamond)
5. Imagine two figures in which bases and the heights are the same; i.e., they are equal. Must the areas also be equal? (no)
6. The hands of a clock are at right angles to each other and the hour hand points to 12. What two times are possible? (11:45, 12:15)
7. If I give you a lot of right angle triangles which all have equal sides, one to the other, how many will you need to make up a square? (2)
8. How many squares of the same size will I need to make a bigger square? (4)
9. If I am facing the door and I turn right to the window and then after that I turn right around (about face), which way will I have to turn to face the door again? (right)
10. On a 3 × 3 checkerboard there are 9 squares. A counter starts in one corner and moves a square at a time round the edge till it gets back to where it began. How many moves must it make to do so? (8)
11. If I take a small printed letter ''b'' and rotate it clockwise till it is upside down, what letter will it be now? (q)
12. If I have two squares and the length of the side of one is twice that of the length of the side of the other, smaller square, how many small squares would fit into the big square? (4)

shortened testing time (Rey: one or two nondyslexic scores missing on a few of the Rey measures; Archimedes Screw: two nondyslexic scores missing; Spatial Word Problems: one dyslexic score missing; Matrices, Woodcock: one nondyslexic score missing; Spelling, Rapid Auditory Naming measures: two dyslexic scores missing; Auditory Analysis Test: one nondyslexic and one dyslexic score missing).

Results

Reading Measures

A series of one-way ANOVAs by group were performed on each reading measure to determine that our dyslexic population was significantly impaired in reading rela-

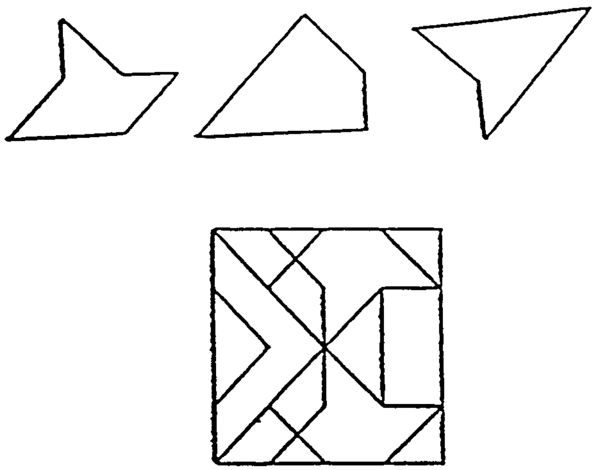

FIG. 6. Sample item, revised Hidden Figures Test, Study 2. The task is to outline the simple shape embedded in the complex one. The shape on the top left is embedded in the lower right of the complex figure.

tive to our control group. Mean scores on each measure are reported in Table 5. As in Study 1, on all measures, the dyslexic group performed significantly worse.

Nelson–Denny Reading Test

On the Nelson–Denny, dyslexics had slower reading rates, $F(1, 33) = 6.544$, $MS_e = 2512.862$, $p = .0155$.

Spelling

On the spelling subtest of the DAR, dyslexics achieved lower levels, $F(1, 34) = 51.478$, $MS_e = 3.913$, $p = .0001$. A comparison of Tables 5 and 1 shows that the dyslexic group in Study 2 was considerably worse in spelling, suggesting that this group was more impaired than in Study 1.

Auditory Analysis Test

On the Auditory Analysis test, dyslexics achieved lower scores, $F(1, 33) = 25.528$, $MS_e = 19.273$, $p = .0001$.

Woodcock Reading Mastery Tests

Dyslexics performed worse on all subtests of the Woodcock: Visual-Auditory, $F(1, 35) = 7.963$, $MS_e = 83.081$, $p = .007$; Letter Identification, $F(1, 35) = 16.032$, $MS_e = 1.299$, $p = .0003$; Word Identification, $F(1, 35) = 50.668$, $MS_e = 79.58$, $p = .0001$; Word Attack, $F(1, 34) = 32.424$, $MS_e = 23.03$, $p = .0001$; and Comprehension, $F(1, 33) = 63.571$, $MS_e = 40.782$, $p = .0001$.

Rapid Naming Tests

On all of the rapid naming tests, dyslexics were significantly slower: Objects, $F(1, 33) = 23.724$, $\mathrm{MS}_e = 34.576$, $p = .0001$; Colors, $F(1, 33) = 36.402$, $MS_e = 36.375$, $p = .0001$; Numbers, $F(1, 33) = 11.02$, $MS_e = 36.654$, $p = .0023$; Letters, $F(1, 33) = 27.782$, $MS_e = 25.749$, $p = .0001$; Numbers + Letters, $F(1, 33) = 20.439$, $MS_e = 55.183$, $p = .0001$; and Numbers + Letters + Colors $F(1, 33) = 12.849$, $MS_e = 131.715$, $p = .0011$.

Visual Spatial Measures

Two-way, Group × Sex ANOVAs were performed on the spatial measures.

Vandenberg Test of Mental Rotation

A two-way Group × Sex ANOVA on the Vandenberg scores revealed a main effect of group, $F(1, 33) = 26.642$, $MS_e = 23.412$, $p = .0001$. Replicating the findings of Study 1, dyslexic participants achieved lower scores. There was also a main effect of sex, $F(1, 33) = 9.87$, $MS_e = 23.412$, $p = .0035$. This occurred because males performed better than females, again replicating the results of Study 1. There was no Sex × Group interaction. The near interaction of Sex × Group in Study 1 was not replicated, and when the analysis was performed without the females, the dyslexic performance remained significantly lower than that of the control group. Mean scores are shown in Table 6.

All participants attempted all of the 20 items. However, dyslexics spent less time

TABLE 5
Mean Scores and Standard Deviations on Reading Tests, Study 2

Test	Dyslexic *M* (*SD*)	Nondyslexic *M* (*SD*)
Nelson–Denny Reading Rate	188.1 (27.5)	233.3 (59.7)
DAR Spelling	6.3 (2.8)	11.3 (1.3)
Auditory Analysis Test	29.1 (6.2)	36.9 (2.8)
Woodcock Visual-Auditory	116.1 (11.1)	124.8 (7.5)
Woodcock Letter Identification	48.9 (1.5)	50.5 (0.8)
Woodcock Word Identification	78.5 (13.4)	100.0 (3.1)
Woodcock Word Attack	31.9 (6.8)	41.3 (2.9)
Woodcock Comprehension	42.4 (8.9)	60.1 (3.8)
RAN Objects	40.3 (8.7)	30.2 (3.2)
RAN Colors	41.6 (7.5)	28.8 (4.9)
RAN Numbers	25.2 (8.9)	18.1 (3.3)
RAN Letters	26.3 (7.4)	16.9 (2.8)
RAS Numbers + Letters	30.7 (11.5)	18.8 (2.9)
RAS Numbers + Letters + Colors	38.3 (13.9)	23.8 (9.7)

solving this task (X = 4 min., *SD* = 2.2 min.) than did nondyslexics (X = 5.4 min., *SD* = 2.0 min.). A two-way ANOVA revealed that this difference approached significance, $F(1, 33) = 3.287$, $MS_e = 16067.229$, $p = .07$. No effects of sex were found. (The large MS_e reflects the fact that the time was recorded in seconds.) Thus, the results of Study 1 were replicated. The dyslexic group performed worse on the Vandenberg, despite the fact that the test was administered without time restrictions.

Rey–Osterrieth Complex Figure Test: Organization Scores

Two-way Group × Sex ANOVAs were performed on Organization scores in the Copy, Immediate Recall, and Delayed Recall Conditions of the Rey–Osterrieth test. As in Study 1, there was no effect of group or sex in the Copy condition. Contrary to prediction, in the Immediate Recall Condition, the dyslexic group (X = 6.3, *SD* = 3.5) had poorer organization scores than did the control group (X = 9.0, *SD* = 4.2), but the difference did not quite reach significance, $F(1, 33) = 3.533$, $MS_e = 16.289$, $p = .069$. There was no effect of sex. Contrary to prediction, in the Delayed Recall Condition, the most difficult task, the dyslexic group again performed worse (X = 6, *SD* = 3.3) than the control group (X = 9.1, *SD* = 4.3), and this difference was significant, $F(1, 32) = 4.519$, $MS_e = 16.092$, $p = .0413$. There was no effect of sex.

TABLE 6
Mean Scores and Standard Deviations on the Vandenberg Test of Mental Rotation, Study 2

Total score (of 20)	Dyslexic *M* (*SD*)	Nondyslexic *M* (*SD*)
Female	4.7 (1.6)	11.1 (6.5)
Male	7.8 (4.9)	18.5 (1.4)
Total	6.5 (13.8)	13.8 (6.3)

Rey–Osterrieth Complex Figure Test: Style Scores

One-way chi-square tests examined the effects of group on the frequency of use of Configurational versus Intermediate or Part-Oriented styles. Contrary to prediction, Configurational styles were less common in the dyslexic than the control group in the Copy condition, $\chi^2(2) = 6.882$, $p = .032$. Seventy-three percent of the control groups' copies, but only 60% of those in the dyslexic group, were classified as Configurational. Configurational styles were also less common in the dyslexic group in both recall conditions, and this difference was significant in the Delayed Recall Condition, $\chi^2(2) = 6.44$, $p = .04$. In the Immediate Recall Condition, 60% of the drawings in the dyslexic group and 82% of those in the control group were classified as Configurational; in the Delayed Recall Condition, only 40% of the drawings in the dyslexic group were scored as Configurational, in contrast to 81% of those in the control group.

As in Study 1, no analyses were performed on Structural Accuracy scores in the Copy Condition because all but two participants achieved a perfect score. In the Immediate Recall Condition, the results of Study 1 were replicated: the dyslexic group performed worse (X = 21.7, $SD = 3.0$) than the control group (X = 24.1, $SD = 2.2$). This difference reached significance, $F(1, 33) = 6.691$, $MS_e = 6.461$, $p = .0143$. There was no effect of sex. In the Delayed Recall Condition, the dyslexic group also achieved lower scores (X = 20.9, $SD = 3.6$) than did the control group (X = 24.2, $SD = 2.0$), and this difference also reached significance, $F(1, 32) = 12.045$, $MS_e = 7.898$, $p = .0015$. Again there was no effect of sex.

Archimedes' Screw

One-way chi-square tests investigated the effect of Group on the four Archimedes Screw questions. There was no effect of Group for the Function Question: both groups were equally likely to recognize the function of the screw. There was also no effect of group for Turn Question 1. However, for Turn Question 2, while all of the nondyslexics responded correctly, only 80% of the dyslexics did so, and this difference proved significant, $\chi(1) = 4.375$, $p = .0365$. In contrast, on Turn Question 3, the most difficult question because it involved overriding a misleading cue, the dyslexic group performed better. While 53% of the dyslexics responded correctly, only 25% of the nondyslexics did so, but this difference only approached significance, $\chi^2(1) = 2.947$, $p = .086$.

Pyramid Puzzle

The pyramid puzzle proved to be near to impossible for all participants, even with the hint. Only one dyslexic and two nondyslexic students completed the puzzle without the hint and providing the hint did not lead to any more students solving the puzzle. Because of this floor effect, no analyses were carried out.

Hand Drawing

As mentioned above, hand drawings were classified as showing some talent, as average, or as primitive by two independent judges blind to whether the drawing was by a dyslexic or a nondyslexic participant. One of the two judges classified 12 of the drawings as showing some talent; the second judge was more conservative and classified only 6 as showing some talent. However, all of the 6 designated by the second judge as showing talent had also been classified in this way by the first judge. We thus selected the 6 on which the two judges agreed and considered these the ‘‘talented’’ drawings. One of the two judges rated 16 of the drawings as primitive; the other judge classified 20 as primitive. Between the two of them, they agreed on 15 of the drawings as primitive.

Of the 6 drawings classified by both judges as talented, 2 were by dyslexics and 4 were by control participants. Thus, 13% of the dyslexic group and 18% of the control group showed some artistic talent. Of the 15 drawings classified by both judges as primitive, 8 were by dyslexics and 7 were by control participants. Thus, 53% of the dyslexic drawings and 32% of the control drawings were classified as primitive. Chi-square tests revealed no differences between groups in terms of level of drawing ability. Thus, despite their overrepresentation in art schools, individuals with dyslexia were showed no more drawing ability than did those without dyslexia. Figure 5 shows examples of primitive and talented drawings by participants from both groups.

Spatial Word Problems

A Group × Sex ANOVA performed on the Spatial Word Problem scores revealed a main effect of group, $F(1, 32) = 18.459$, $MS_e = 3.704$ $p = .0002$. Contrary to hypothesis, dyslexic students had lower scores ($X = 3.7$, $SD = 2.1$) than did the nondyslexic students ($X = 6.5$, $SD = 1.9$). There was no effect of sex.

K-BIT Matrices

A Group × Sex ANOVA performed on the matrices of the K-BIT revealed a main effect of group, $F(1, 32) = 9.96$, $MS_e = 17.865$, $p = .0035$. Contrary to prediction, the dyslexic group performed worse ($X = 34.1$, $SD = 5.5$, $n = 15$) than the control group ($X = 38.7$, $SD = 3.0$, $n = 21$), and there was no effect of sex.

Hidden Figures

A two-way Group × Sex ANOVA revealed no main effects and no interaction on the Hidden Figures test. Thus, results of Study 1 were replicated: The dyslexic group did not perform any better than the control group.

Discussion

Despite the fact that in Study 2 we used more real-world tasks and administered them without time constraints, we were unable to demonstrate any consistent spatial advantage for individuals with dyslexia. Individuals with dyslexia again performed below control participants on the Vandenberg (and in Study 2 this was true of both sexes), and they spent less time on this task, suggesting either that they falsely believed they were doing well, or that they recognized the difficulty and expended less effort as a result, or that they traded accuracy for speed. On the Rey–Osterrieth, individuals with dyslexia performed less well in level of Organization, were less likely to draw the figure in a Configurational style, and had lower Structural Accuracy scores. They also performed worse than control participants on the spatial word problems, the matrices, and Turn Question 2 of the Archimedes Screw task. Only on the final (and presumably most difficult question) of the Archimedes task did individuals with dyslexia outperform the control group, but this difference did not reach significance. They performed equivalently to the control group on the Hand Drawing and Hidden Figures tasks. Thus, dyslexic individuals did not show an advantage on any spatial measure.

It is possible that the finding of no superiority by the dyslexic group on the spatial measures was due to the fact that the dyslexic participants were in high school and thus had less test-taking experience than the members of the control group, who were in college. Thus, in Study 3 our control group was matched to the dyslexic group in age (both groups were high school students). It is also possible that our failure to demonstrate superiority was due to insufficient sampling of spatial skills. Perhaps we did not administer tasks assessing the kinds of visual-spatial skill in which dyslexics may excel. Hence, in Study 3 we administered a far wider range of visual-spatial tests. The tasks administered were chosen to reflect the major types of visual-spatial abilities that have been identified in factor-analytic research (Carroll, 1993). In addition, we developed a task modeled after the Morris Maze task on which ectopic mice have been shown to excel (Waters et al., 1997) in order to determine whether the kind of spatial reference memory assessed by this task in one on which individuals with dyslexia excel.

STUDY 3

Method

Participants

A total of 63 high school students participated in Study 3. Forty had been diagnosed as dyslexic (28 males, 12 females) and attended a school for students with language-based learning disabilities. This school was similar to the one from which students were drawn in Study 2. All but one high school student in this school chose to participate, thus eliminating the possibility of a selection bias. The control group consisted of 23 high school students with no previous diagnosis of dyslexia or any other type of learning disability (13 males, 10 females). These students attended an ordinary suburban public high school. Students from both schools came from middle- and upper- middle-class backgrounds. Dyslexic students were paid $30 for their participation. Due to funding limitations, nondyslexic students were paid only $10 for their participation.

Materials and Procedure

No reading measures were administered since all dyslexic students had been previously diagnosed with dyslexia and so that we would have time to administer more spatial tests. Tasks were designed to assess four major kinds of spatial ability as identified by factor analytic methods (Carroll, 1993): spatial orientation, spatial visualization, figural flexibility, and closure speed. In addition, we developed another test designed to assess the kinds of abilities assessed by the Morris Maze task described above, on which ectopic mice excelled.[3]

All but one task were administered in groups of 10–20 students. The Gestalt Completion Test was administered individually because participants are required to speak aloud. For all but the Gestalt Completion Test, participants were asked to indicate where they were after the standard time period for the test was up. However, we allowed participants to continue for as long as they needed. Participants then received two scores for each test: score on the timed portion, and total score disregarding where they were when time was called. For the Gestalt Completion Test, participants were given as much time as needed, with no cutoff point.

Finally, to determine whether attentional deficits might be responsible for poor spatial performance, parents were asked whether their child had ever had a diagnosis of an attentional deficit. Participants were classified as having an attentional deficit or not based on this measure.

Spatial Measures

Spatial Orientation. Spatial Orientation involves the ability to imagine how an image will appear from another perspective (Carroll, 1993). Three tests were administered to assess this ability.

The Card Rotation Test assessed the ability to imagine a two-dimensional array from another perspec-

[3] Several other tasks were also administered to the same participants for use in two other related studies (Malinsky, submitted; von Károlyi, in press).

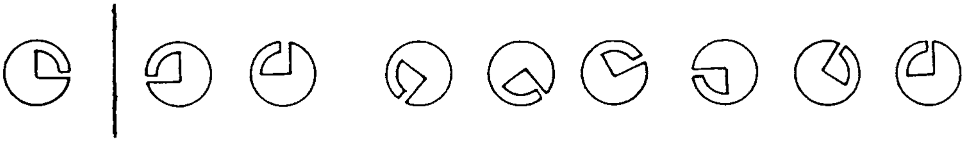

FIG. 7. Sample Card Rotation Test item, Study 3. The task is to determine which of a set of eight two-dimensional shapes are rotated versions of the target shape on the left. Reprinted by permission of Educational Testing Service, the copyright owner.

tive (Ekstrom et al., 1976). As shown in Fig. 7, in this task one must compare an array of two-dimensional shapes to a target and decide which of the shapes are rotated versions of the model. Score was determined by number of correct responses. We asked participants to indicate where they were after three minutes by placing a mark. We then allowed them to continue for as long as needed.

The Vandenberg Test of Mental Rotation (Part 1) was again administered (Vandenberg & Kuse, 1978). We asked participants to indicate where they were after 3 min by placing a mark. We then allowed them to continue for as long as needed. This task was scored in the same way as in Study 2, which corrected for guessing.

The Boats Test assessed the ability to imagine how a landscape would look from an altered orientation (Guilford & Zimmerman, 1953), a skill that would seem to be associated with navigational skill. In this (very difficult) task, participants are presented with a landscape scene viewed from the front of a speedboat. Below this scene is a second scene reflecting a change in the boat's position. The task is to determine how the position of the boat has changed, given the changed view. As shown in Fig. 8, position of the boat is demonstrated by selecting one of five diagrams representing the change in the boat's position. The standard time period for this test is 4 min: Participants marked where they were at 4 min and then continued. Score was determined by number correct.

Spatial Visualization. Spatial Visualization involves the ability to apprehend, encode, and mentally manipulate spatial forms (Carroll, 1993). The Form Board Task (Ekstrom et al., 1976) was administered to assess this capacity. In this task, a geometric design is presented along with five shapes underneath the design, as shown in Fig. 9. The task is to indicate which of the five pieces, when put together, would form the top design. The standard time period for this test is 4 min: Participants marked where they were at 4 min and then continued. Score was determined by number correct.

Figural Flexibility. Figural Flexibility involves the ability to come up with a variety of ways to solve a spatial problem (Carroll, 1993). The Storage Task (Ekstrom et al., 1976) was administered to assess this capacity. Participants are given a drawing of a three-dimensional cubic space and are asked to show (by drawing) as many different ways as possible in which to arrange rectangular objects in this space, as shown in Fig. 10. The standard time period for this test is 3 min: Participants marked where they were at 3 min and then continued. Different variants of the same solution were awarded one point; different kinds of solutions were awarded 2 points each.

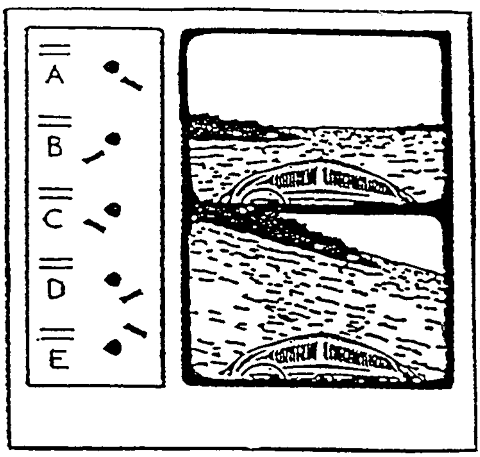

FIG. 8. Sample Boats item, Study 3. The task is to select the diagram on the left indicating how the position of the boat in the lower picture has changed relative to its position in the top picture.

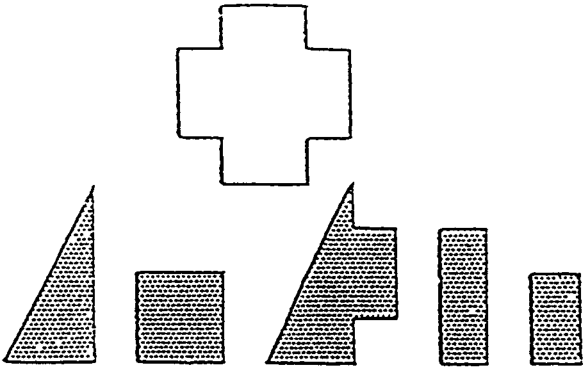

FIG. 9. Sample Form Board item, Study 3. The task is to indicate which of the five shaded shapes, when put together, would form the unshaded target shape (correct = 1, 3, and 5). Reprinted by permission of Educational Testing Service, the copyright owner.

Closure Speed. Closure Speed involves the ability to unite an apparently disparate perceptual field into a unified concept (Carroll, 1993). The Gestalt Completion Test (Ekstrom et al., 1976) was administered to assess this capacity. This test assesses the ability to access spatial representations in long-term memory given only partial cues. As shown in Fig. 11, participants see an incomplete drawing of a familiar object and are asked to identify the object as quickly as possible (by saying its name). Performance is scored separately for number correct and speed. The score for speed was computed by dividing the time to complete all items by the number of correct identifications. Participants were told to work as quickly as possible but they were given as much time as needed.

Reference Memory. A Reference Memory task was developed to assess the kind of spatial memory assessed by the Morris Maze test. Participants were asked to imagine themselves facing in a particular direction and standing at a particular place in one of their school buildings (e.g., with their back to the door to the third-floor elevator). They were then asked to imagine pointing toward another location in their school (e.g., from where you are now standing, point to the door of the gym). Participants indicated the direction in which they would point by marking an X on a circle, as shown in Fig. 12. Like the Morris Maze task, this task assesses the ability to recall the spatial relation between two landmarks, the one at which one is standing and the one to which one is pointing. Score was computed by averaging the top four scores of five (so that one poor performance would not lower overall score).

Results

Attention

A chi-square analysis demonstrated that dyslexic participants were more likely to have received a previous diagnosis of an attentional deficit, $\chi^2(1) = 10.23$, $p = .001$. Sixty-eight percent of the dyslexics, but only 22% of the nondyslexics, had received such a diagnosis.

Spatial Measures

A series of three-way, Group × Sex × Attention ANOVAs were performed on scores received on each spatial measure (both timed and untimed). Inclusion of attention as a factor allowed us to determine whether poor performance on the part of the dyslexic group, if found, could be due to the greater frequency of attentional problems in the dyslexic group. Simple effects analyses were performed to explain any interactions found. Unless noted, all analyses are based on an N of 58. (A few participants did not take all the tests due to constraints in school scheduling.)

Spatial Orientation

Card Rotation, timed. On the timed version of the Card Rotation Test, there was a main effect of group, $F(1, 50) = 5.66$, $MS = 3219.45$, $p = .021$. This occurred

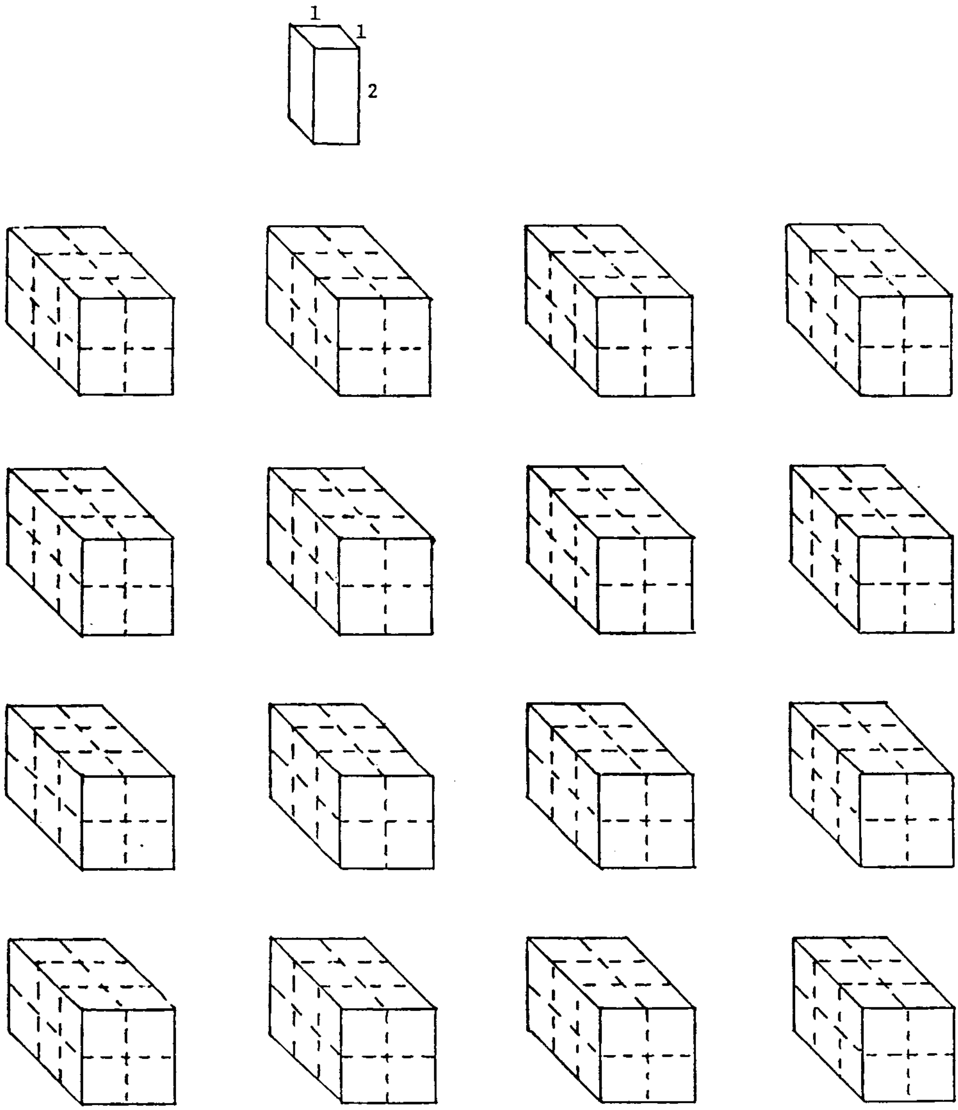

FIG. 10. Sample Storage item, Study 3. The task is to indicate all of the ways to arrange six rectangular boxes in a given container. Reprinted by permission of Educational Testing Service, the copyright owner.

because dyslexics performed worse, $M = 43.25$ versus 62.556. There were no other main effects or interactions.

Card Rotation, untimed. On the untimed version of the Card Rotation Test ($N = 57$), there was also a main effect of group, $F(1, 49) = 5.54$, $MS = 3511.55$, $p = .023$. Again the dyslexics performed worse, $M = 53.462$ versus 77.333).

Thus, dyslexics' performance on this test was not enhanced by eliminating time constraints. Nor did attention predict performance on this test; hence, dyslexics' poor performance is not a function of the greater frequency of attentional problems among the dyslexic group.

Vandenberg, timed. On the timed version of the Vandenberg, there was no main effect of group, though dyslexics performed somewhat worse than nondyslexics, $M = 8.775$ versus 10.889. There was a main effect of sex, $F(1, 50) = 10.82$, $MS = 221.66$, $p = .002$. This occurred because males performed strikingly better, $M = 11.026$ versus 6.4. There were no other main effects or interactions.

FIG. 11. Sample Gestalt Completion item, Study 3. The task is to identify the object that is incompletely depicted. In this case, a flag. Reprinted by permission of Educational Testing Service, the copyright owner.

Vandenberg, untimed. On the untimed version of the Vandenberg, there was a significant effect of group, $F(1, 50) = 5.58$, $MS = 122.10$, $p = .022$. Again dyslexics performed worse, $M = 9.750$ versus 14.222. There was again a main effect of sex, $F(1, 50) = 10.29$, $MS = 225.15$, $p = .002$. This occurred because males performed better, $M = 12.605$ versus 8.350. Thus, dyslexic's performance on this test was actually reduced relative to nondyslexics when time constraints were eliminated, suggesting that nondyslexics could take advantage of the unlimited time, but dyslexics could not. As with the Card Rotation test, attention did not predict performance on this test.

Boats, timed. On the timed version of Boats, there was no effect of Group. There was, however, a significant effect of sex, $F(1, 50) = 13.52$, $MS = 256.04$, $p = .001$. This occurred because males performed better than females, $M = 10.737$ versus 6.55.

Boats, untimed. On the untimed version ($N = 55$), there was a main effect of Group, $F(1, 47) = 15.01$, $MS = 263.42$, $p < .001$. This occurred because dyslexics performed worse than nondyslexics, $M = 9.795$ versus 15.688. There was also a main effect of sex, $F(1, 47) = 19.43$, $MS = 340.99$, $p < .001$. This occurred because males performed better than females ($M = 12.889$ versus 8.895). Dyslexia interacted with sex, $F(1, 47) = 5.78$, $MS = 101.39$, $p = .02$. A simple effects analysis examined the effects of dyslexia within sex. A two-tailed t test on males revealed that dyslexics performed significantly worse, $t(36) = 5.60$, $p = <.001$ ($M = 10.704$ versus 19.546).

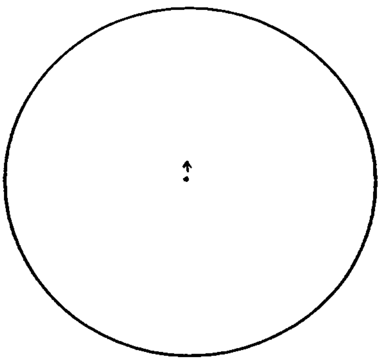

FIG. 12. Sample Reference Memory item, Study 3. The task is to imagine oneself at a familiar spot (represented by the dot in the middle of the circle), facing in a given direction (represented by the arrow) and then to indicate, by marking an X on the circle, the direction to another familiar landmark.

The same test on females also revealed that dyslexics performed significantly worse, $t(18) = 2.55$, $p = .02$ ($M = 7.750$ versus 11.625). As can be seen from the means, the difference between dyslexics and nondyslexics is greater in males than females, which accounts for the interaction found. However, the difference was greater in males not because the male dyslexics were worse than the female dyslexics, but rather because the female controls achieved lower scores than the male controls.

Again we see that dyslexics' performance was reduced relative to nondyslexics when time constraints were eliminated, suggesting that nondyslexics could take advantage of the unlimited time, but dyslexics could not. And again we see that attention did not affect performance on this test.

Spatial Visualization

Form Board, timed. On the timed version of the Form Board Test, there was no effect of group or attention. There was a main effect of sex, $F(1, 50) = 7.69$, $MS = 3026.12$, $p = .008$. This occurred because males performed better than females ($M = 59.447$ versus 49.5). The only interaction was a three-way, Group × Sex × Attention, $F(1, 50) = 4.74$, $MS = 1867.37$, $p = .034$.

To understand this interaction, we performed a two-way Group × Attention ANOVA for males and females separately. For females ($N = 20$), the two-way Group × Attention ANOVA revealed no main effects or interactions. For males ($N = 38$), there was a near-significant interaction of Group × Attention, $F(1, 34) = 3.29$, $MS = 1516.86$, $p = .079$. It was not possible to perform a one-way, within-attention *t* test to explain this interaction, since there were only two nondyslexic males without a diagnosis of an attentional problem. However, an examination of the means revealed that the interaction occurred for the following reason. Among dyslexics, those with attentional problems performed worse than those without ($M = 54.105$ versus 64.444). But among nondyslexics, those with attentional problems actually performed better than those without. Thus, on this task attentional problems appear to affect dyslexic and nondyslexic individuals differentially, but this effect only occurred for males.

Form Board, untimed. On the untimed version of the Form Board Test, there was a near significant effect of group, $F(1, 50) = 3.70$, $MS = 1753.95$, $p = .06$. This occurred because dyslexics performed worse, $M = 64.85$ versus 80.222). There was a main effect of sex, $F(1, 47) = 16.37$, $MS = 3019.17$, $p = .015$. This occurred because males performed better ($M = 72.947$ versus 63.300). There were no significant interactions.

Figural Flexibility

Storage, timed. On the timed version of the Storage Test ($N = 54$), dyslexics performed worse than nondyslexics ($M = 5.47$ versus. 7.67), but this difference only approached significance at $p = .078$. There was a main effect of sex, $F(1, 46) = 8.86$, $MS = 52.16$, $p = .005$. This occurred because males performed better ($M = 6.735$ versus 5.3). Sex interacted with group, $F(1, 44) = 5.57$, $MS = 32.77$, $p = .023$. To understand this interaction, a *t* test was performed for males and females separately, with group as the factor. For males, there was a significant effect of group, $t(35) = 3.89$, $p < .001$. This occurred because dyslexics performed worse ($M = 5.625$ versus 9.231). For females, there was no effect of group ($M = 5.8$ for the dyslexics versus 5.17 for the control group). However, a comparison of means across groups and by sex shows that the male and female dyslexics performed equivalently and that the interaction was due to higher scores in the male control group than in the female control group.

Storage, untimed. On the untimed version of the Storage Test ($N = 50$), there was no significant effect of group, although dyslexics achieved lower scores than did nondyslexics ($M = 9.88$ versus 13.47). There was a main effect of sex, $F(1, 42) = 7.55$, $MS = 152.84$, $p = .009$. This occurred because males performed better ($M = 11.936$ versus 9.737). There was a main effect of attention, $F(1, 44) = 4.67$, $MS = 94.46$, $p = .037$. This occurred because those with an attentional problem performed worse ($M = 9.320$ versus 12.880). Sex interacted with group, $F(1, 44) = 8.66$, $MS = 175.41$, $p = .005$.

To understand this interaction, two within sex t test were performed. For males ($N = 34$), dyslexics were significantly worse than nondyslexics, $t(32) = 3.80$, $p = .001$. For females ($N = 21$), there was no effect of group, and dyslexics performed nearly as well as nondyslexics ($M = 9.818$ versus 10.3). However, a comparison of means shows that male and female dyslexics performed equivalently ($M = 9.9$ versus 9.8, respectively). The interaction was again due to the fact that male control participants scored higher than female control participants ($M = 16.0$ versus 10.3).

Closure Speed

Gestalt Completion, number correct. On the total number correct on Gestalt Completion Test ($N = 57$), there was no effect of group, and dyslexics performed identically to nondyslexics [$M = 14.103$ (dyslexics) versus 14.111 (nondyslexics)]. There was an effect of sex, $F(1, 49) = 4.14$, $MS = 16.84$, $p = .047$. This occurred because males performed better ($M = 14.395$ versus 13.526).

Gestalt Completion, reaction time. An analysis was next performed on the total time taken on the Incomplete Figures Test, divided by the number correct ($N = 52$). There was no effect of group, and dyslexics performed almost as well as nondyslexics ($M = 8.768$ versus 10.126). There was an effect of sex, $F(1, 44) = 4.88$, $MS = 60.68$, $p = .032$. This occurred because males performed better ($M = 10.471$ versus 8.585). There was an effect of attention, $F(1, 44) = 4.59$, $MS = 57.03$, $p = .038$. This occurred because those with attentional problems performed worse ($M = 8.413$ versus 10.129). There were no significant interactions.

Spatial Reference Memory

On the Reference Memory Test, there was a main effect of group, $F(1, 50) = 7.86$, $MS = 1425.98$, $p = .007$. This occurred because dyslexics performed worse: dyslexics missed the target by a mean of 24.251 degrees; nondyslexics missed the target by only 11.192 degrees. Thus dyslexics' responses were twice as far off target as nondyslexics.

Discussion

On only three measures did we find an effect of attention: on the untimed score of the Storage Task, on the timed version of the Form Board Test (but only for males), and on the reaction time score of the Gestalt Completion Test. In no case did attention diagnosis interact with group. Thus, we did not find that those dyslexics with attentional problems were the ones who performed poorly (with the exception of the male dyslexics on the timed Form Board).

Individuals with dyslexia performed worse than those without dyslexia on all three spatial orientation tasks (including on the Vandenberg, which represents the second replication of the finding from Study 1). Individuals with dyslexia performed equivalently to those without dyslexia on the spatial visualization tasks (though they performed worse on the Form Board task when it was untimed). And the two groups performed equivalently on the Closure Speed tasks.

Individuals with dyslexia performed worse than those without on the Reference Memory task. This result was surprising, given that this type of task is one on which mice with ectopias perform well. However, our task may well be different from the Morris Maze task in crucial respects. The Reference Memory task used here required participants to imagine themselves in a particular position, and these instructions were given verbally. This task may thus have required working memory as individuals manipulated their mental representation of their spatial location. In contrast, of course, the Morris Maze task is a nonverbal task that does not require imagining oneself in a hypothetical position. It is precisely tasks that require working memory that have been shown to be impaired in mice with ectopias. (Boehm et al., 1996; Waters et al., 1997).

The poor performance of individuals with dyslexia cannot be explained by time constraints. When unlimited time was allowed, either performance was not altered compared to the nondyslexic group or performance by the dyslexic group actually became comparatively worse. Apparently, individuals without dyslexia were able to make use of extra time, perhaps to check answers, or simply to go further, while those with dyslexia did not make profitable use of the extra time. Perhaps they make errors when they go back and check answers, perhaps they do not go back and check, or perhaps they simply get weary and stop trying.

While some interactions with sex and group were found, these occurred because within the control group, males performed better than females. We were unable to replicate the finding in Study 1 of female dyslexics performing worse than male dyslexics. It is possible that the dyslexic brain is so variable (recall the variability in extent and location of ectopias) that individual differences in spatial ability among dyslexics outweigh any differences due to sex. However, despite individual variations among dyslexics, Study 3 did not reveal any talents among those with dyslexia.

GENERAL DISCUSSION

Our research suggests that individuals with dyslexia do not excel on visual-spatial tasks. Rather, they perform worse than or equivalently to individuals without dyslexia on such tasks. How can these results be explained, given the disproportionate representation of individuals with dyslexia in spatial fields?

One possible explanation is that individuals with dyslexia choose spatial professions not because of a spatial talent, but by default, because verbal professions are closed to them (cf. Winner, Casey, DaSilva, & Hayes, 1991). Suppose that, as our results suggest, dyslexia is associated with impaired spatial as well as reading-related abilities. Despite this dual impairment, it is highly likely that impairments in reading are far more severe and disabling than the spatial impairments. Individuals with dyslexia might therefore select spatial occupations in order to *avoid* fields which require extensive reading, such as law, medicine, history, and so on.

Suppose also that, as some of our results suggest, dyslexia is associated with average rather than deficient spatial abilities. If so, the distribution of spatial talents in the dyslexic population should be no different from the distribution in the nondyslexic population. Hence, there should be a subset of individuals with dyslexia with spatial talents, and this subset should be proportionally equivalent to the subset of non-reading-disabled individuals with such talents. While nondyslexics with spatial talents might be as likely to choose a verbal as a spatial occupation (since both avenues are open to them), dyslexics with spatial talents would not have the luxury of this choice. Dyslexics with spatial talents would again choose spatial professions by default. Hence, we would find a disproportionate incidence of dyslexic individuals channeled into spatial fields, but no differences in spatial abilities in dyslexics versus nondyslexics.

This latter account is consistent with a view of the brain as relatively modular in organization (Gardner, 1983). Given a modular brain, dyslexia should have no effect on non-reading-related skills. The manifestation of talents in spatial areas should thus be equivalent in rate in both dyslexic and nondyslexic populations.

Before we conclude, however, that individuals with dyslexia do not have spatial talents, we believe that further research is needed. To begin with, on one task our dyslexic group did show superior (though not significantly superior) performance—on the difficult Archimedes screw question. This finding should be replicated to determine whether it reaches significance with a larger sample of dyslexics. In addition, other tasks assessing the same kind of spatial visualization ability as the Archimedes task should be developed in order to test the generalizability of this finding.

Second, despite our attempt in Study 2 to make our spatial tasks more ecologically valid, we believe that more real-world, three-dimensional, hands-on spatial tasks should be developed. In Study 3 we added a navigational task (Boats). However, because this task was presented as a paper-and-pencil task, it may not have been a genuinely spatial measure of navigational skills.

Third, it is possible that there is a spatial advantage in dyslexia but that this advantage shows up only in the right tail of the distribution (as does the male advantage in math) (Benbow, 1988). Perhaps we did not have enough dyslexics in our sample to detect those at the right tail of the spatial distribution. Thus, studies with far larger sample sizes are required to test this possibility. A larger population of dyslexics would also allow us to test whether there is a particular subgroup of dyslexics with spatial talents.

While spatial tasks often have attentional components, and while individuals with dyslexia often have attentional problems, the attentional components of the tasks cannot account for the poor performance by dyslexics. This conclusion is based on the finding that dyslexics without diagnosed attentional problems did no better on our tasks than those with such a diagnosis.

In sum, the three studies reported here consistently fail to provide any support for the compensation model of dyslexia. Across a wide variety of two- and three-dimensional spatial tasks, including those presented without time constraints, we remained unable to demonstrate any kind of spatial advantage in individuals with dyslexia. Our studies do not support the popular (and comforting) view of dyslexia as a deficit associated with compensatory talents.

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