Longitudinal Twin Study of Early Reading Development in Three Countries: Preliminary Results

Brian Byrne
Cara Delaland
Ruth Fielding-Barnsley
Peter Quain
University of New England, Australia

Stefan Samuelsson
Torleiv Høien
Stavanger College, Norway

Robin Corley
John C. DeFries
Sally Wadsworth
Erik Willcutt
Richard K. Olson
University of Colorado
Boulder, Colorado

We have initiated parallel longitudinal studies in Australia (Byrne, PI), the United States (Olson, PI), and Norway (Samuelsson, PI) of identical and fraternal twins who are being tested in preschool for pre-reading skills, and in kindergarten, first grade, and second grade for the development of early reading, spelling, and related cognitive skills. Comparisons of the similarities of identical and fraternal twins will reveal the relative influence of genetic, shared family environment, and

Annals of Dyslexia, Vol. 52, 2002

ISSN 0736-9387

nonshared environment on individual differences at and across different stages of development. Family and twin-specific environmental information is also being directly assessed through parent questionnaires and observations by testers. Most of the data collected so far have been from preschool twins (146 in Australia, 284 in the United States, and 70 in Norway). Preliminary analyses for the preschool cognitive measures showed reliable genetic influences on phonological awareness and several measures of memory and learning. In contrast, vocabulary, grammar, and morphology showed significant shared environment and negligible genetic effects. A print knowledge composite showed both genetic and shared environment influence.

OVERVIEW

It is now well established and widely accepted that individual differences in reading ability are, in part, heritable. Twin-based behavior-genetic studies with reading-disabled, school-aged individuals (DeFries & Alarcon, 1996; Gayán & Olson, 2001), with individuals in the normal range of reading ability (Davis, Knopik, Olson, Wadsworth, & DeFries, 2001), and with high ability individuals (Boada et al., in press) all indicate substantial genetic influence. The genetic effects extend to all aspects of reading including phonological decoding, orthographic knowledge, reading comprehension, and spelling (Olson, Forsberg, & Wise, 1994). Complementing the behavioral observations are studies at the molecular level with reading-disabled individuals and their parents and siblings, with susceptibility genes for dyslexia having been localized to chromosomes 2, 6, and 18 (Fisher et al., 2002; Gayán et al., 1999). Thus, there may be different genetic pathways to dyslexia across different individuals. We should also note that while the genetic influence for dyslexic *group* deficits as well as individual differences in reading and related skills are highly heritable, the relative importance of genetic and environmental factors may vary widely among different individuals with dyslexia and among different individuals across the normal range.

One aim of the present project is to gain a longitudinal perspective on genetic and environmental influences on literacy growth. All behavior-genetic research into literacy growth has so far been cross-sectional with school age children, and although there are indications of differential genetic effects as a function of age for component-skill deficits in reading and spelling (DeFries, Alarcon, & Olson, 1997), longitudinal studies offer the best prospects for identifying age-related trends in the amount and type of genetic and environmental influences. To this end, we elected to begin with preschool-aged twin children prior to their formal introduction to reading in the school system. As well as assessing relevant variables in these four-year-olds as outlined below, we are following the children through the first several years of school to identify growth trends in a behavior-genetic framework. In this paper, we present preliminary data from the preschool phase of the project.

A second aim of this project is to examine genetic and environmental influences on cognitive, linguistic, and behavioral processes that are known to co-vary with reading ability and to do so in a design which may help disentangle causal relations among these processes and literacy levels themselves. Essentially, this means measuring these related processes prior to reading instruction, and particularly prior to reading failure. If processes considered as candidates for explaining variance in reading levels are assessed only after those levels are established, it is difficult to know whether the variables which are, in fact, related to reading skill are to be numbered among the causes or among the effects of reading level, or if indeed are related by means of a common process (Bradley & Bryant, 1983). By assessing candidate processes in young children prior to school entry, there is some assurance that variability in those processes is not due to variability in reading skill. If it further turns out that one or more of those processes shares genetic variance with subsequent reading skill, we may be closer to understanding how genes can influence this culturally determined ability, one that emerged only late in human history (Byrne, 1998; Man, 2000).

The logic of twin studies in estimating genetic influences on behavior is reasonably well known. Briefly, what is of most interest is the degree of correlation for monozygotic (MZ) twins compared to that of dizygotic (DZ) twins. MZ twins have all of their genes in common within pairs whereas DZ twins share, on average, half of their "segregating genes" (i.e., genes that vary across individuals). In contrast to this distinction between genetic similarities for the MZ and DZ twin types, it is assumed that both types have equally similar shared environments, such as the early home situation, although a child's genes may have an effect on his or her environment within the home, since parents respond differently to each child's unique personality and abilities (Segal, 2000). Given these facts and assumptions, any greater similarity between MZ twins compared to DZ twins on the variable of interest can be attributed to genes, and estimates of heritability can be obtained from within-pair covariances or correlations (Neale & Cardon, 1992). The effects of common (e.g., home) environment can also be detected in twin designs. If a behavioral process is largely under the influence of shared environment but not of genes, then the correlation between DZ twin pairs will be high, and similar to that between MZ twin pairs. Finally, nonshared environmental influences are reflected by the degree to which the correlation for MZ twins differs from 1, since shared environment and genetic influence account for the MZ twin correlation.

SELECTING VARIABLES FOR INCLUSION

In deciding on what to include in the assessment of the children and their environments, we were guided by both substantive observations and methodological considerations. Numbered among the former were cognitive and behavioral processes known to correlate with reading ability and/or known to predict reading ability when assessed prior to or during kindergarten. In addition, we included a measure of responsiveness to phonemic awareness instruction as justified below. Methodological constraints included the use of measures free of floor or ceiling effects, of reasonable reliability, and suitable for administration to young children. We also needed to keep the total commitment of the children to manageable proportions. Many colleagues made useful suggestions for measures to include, which, had we done so fully, would have produced an assessment battery too taxing for our young participants.

Some of our measures require little justification because their roles in and relations to reading and reading development are so well known. Phonological awareness is one such measure (for an extended analysis, see Byrne, 1998). Another is verbal working memory (see Swanson & Siegel, 2001, for a review), as is the related process of nonword repetition, which is implicated in vocabulary development and has been shown to distinguish preschool children at familial risk of reading disability from other preschoolers (Gathercole & Adams, 1993; Gathercole & Baddeley, 1989; Hindson, 2001). A fourth is rapid automatized naming (RAN), familiar because it forms one plank of the “double deficit” hypothesis (see Wolf & Bowers, 1999, for a review). Letter knowledge is also an intuitively plausible and empirically grounded predictor of reading growth (Byrne, 1998; Scarborough, 1998), and we additionally included tests of word recognition and environmental print, in part to determine which of our participants were indeed prereaders and in part as an index of the ability to acquire printed symbols from the environment.

The length of the test battery precluded a full assessment of intelligence, so we heeded the advice of Sattler (1988) and selected the Vocabulary and Block Design subtests of the *Wechsler Preschool and Primary Scale of Intelligence* (*WPPSI*) Wechsler, 1989) on which we could base an estimate of IQ. The vocabulary measure was important in its own right because of evidence that variation in vocabulary size is the best predictor of reading achievement, outside of print-specific variables such as letter knowledge, when measured prior to school (Scarborough, 1998). The *WPPSI* calls on the child to provide definitions of lexical items, but the available evidence indicates that it is confrontation naming that has the highest correlation with subsequent reading levels (Byrne, Fielding-Barnsley, Ashley, & Larsen, 1997; Scarborough, 1998), so we added such a test.

Aspects of language other than phonological and lexical processes such as syntactic, morphological, and semantic operations have also been associated with reading achievement as predictors and as simultaneous correlates (Carlisle, 1987; Catts, 1989, 1993; Scarborough, 1991a, b, 1998). Some ways of assessing these processes, such as determining mean length of utterance, involve procedures that were beyond the resources of this project, so we elected to employ a standardized measure of syntactic control, grammatic closure, and a test of morphological processing closely based on the early work of Berko (1958).

Confirmation that many of the variables identified above are suitable candidates for inclusion comes from research with children with family histories of marked reading disability (Byrne et al., 1997; Elbro, Borstrøm, & Petersen, 1998; Gallagher, Frith, & Snowling, 2000; Hindson, 2001; Lyytinen, 1997; Pennington & Lefly, 2001; Scarborough, 1991b). In some of these studies, comparisons between high- and low-risk groups formed the bases for conclusions (e.g., Byrne et al., 1997; Hindson, 2001). In others, additional comparisons were based on reading outcomes of the children themselves once they had been in school long enough to determine which children became reading disabled and which ones did not (e.g., Pennington & Lefly, 2001; Scarborough, 1991b). Compared to preschoolers unburdened by the family risk factor, at-risk children scored lower than the controls in phonological awareness and other aspects of phonological processing such as speech perception and production, nonword repetition, print awareness (letter knowledge and familiarity with book conventions), vocabulary, and verbal working memory. These effects were typically heightened when retrospective comparisons based on reading outcome were made, such that significant differences were found on measures such as preschool print and phonological awareness, and on verbal working memory between high-risk children who became reading disabled and those who did not (e.g., Elbro et al., 1998; Gallagher et al., 2000; Pennington & Lefly, 2001). Aspects of the data also indicated that the risk factor is continuous rather than discrete. For instance, Pennington and Lefly (2001) found that high-risk children who did not become reading disabled nevertheless performed more poorly on certain literacy and phonological processing measures (though not explicit phonological awareness) than low-risk children.

These family data suggest but do not prove the possibility of genetic influence on the children's performance deficits, since children share both genes and environment with their parents. The present study with twins is a powerful way to disentangle the average genetic and environmental influence across the sample.

The cognitive variables introduced so far can be classified as "static" in that they are single-time snapshots of processes (even though these processes are developmentally progressive). But learning to read is, by definition, an act of learning, and we wished to include measures of the learning process itself as in the "dynamic" assessment approach described by Grigorenko and Sternberg (1998). Apart from the intuitive appeal of doing so, there is accumulating evidence that responsiveness to instruction can itself be diagnostic of future reading disability. In the study of at-risk preschool children, Byrne et al. (1997) noted that the children were less responsive to instruction in phoneme identity than a comparable randomly selected group of preschoolers. Phoneme identity involves recognition that two words can begin, or end, with the same phoneme, as in *sun* and *sail* or *dress* and *bus* (see Byrne & Fielding-Barnsley, 1989, 1990). Further, Byrne, Fielding-Barnsley, and Ashley (2000) showed that in those randomly selected preschoolers, responsiveness to the instruction, measured in terms of how quickly each child grasped the notion of phoneme identity, was a good predictor of school progress in reading, even after six years. Consistent with this observation was the fact that children from this sample who were classifiable as reading disabled in Grade 5 required many more lessons than the subsequently nondisabled children to achieve an understanding of phoneme identity during the preschool training phase, even though almost all of them did achieve this understanding and remained secure with it.

Our measures of learning fell into two classes: standardized tests and tailor-made tests. With the former, we sampled acquisition and retention of verbal, symbolic, and visuospatial material. The tailor-made tests involved acquisition of the concept of phoneme identity, chosen because of its crucial role in reading acquisition (Byrne, 1998; Byrne & Fielding-Barnsley, 1989, 1990) and, therefore, for its ecological validity in this behavior-genetic study of prereading skills and early reading growth.

In addition to measures of cognition and learning, we have assessed the children for signs of inattention and hyperactivity. This is important in light of the well-established comorbidity between inattention and reading disability, and of evidence for shared genetic variance, as well as its shared linkage to a gene or genes on the short arm of chromosome 6 (Willcutt et al., 2002).

We have also attempted to index aspects of the home environment that might play a role in literacy development and thereby cause twin-pair resemblance due to shared environmental influences. These aspects included parental educational backgrounds and reading habits, parent-child shared literacy activities, and child-initiated print activities (Scarborough, 1998).

In this preliminary report, we focus on the cognitive and learning variables and, therefore, the attentional and environmental measures will not be described further.

METHOD

PARTICIPANTS

The twins included in the present analyses were ascertained in Australia, Norway, and the United States. All were said by their parents to be in their final preschool year, with ages at initial contact and testing ranging from 47 to 68 months (mean 58.8) in Australia, 54 to 71 months (mean 59.0) in the U.S., and 58 to 67 months (mean 61.3) in the Norwegian sample, where children start formal schooling a year later. The Australian sample of 46 pairs of monozygotic and 27 pairs of same-sex dizygotic preschool twins was selected from the National Health and Medical Research Council's Australian Twin Registry, a voluntary database containing the names of over 30,000 sets of twins. Parents were approached by mail and approximately 60% agreed to participate. No payment was given for participation. The U.S. sample of 63 pairs of monozygotic and 79 pairs of same-sex dizygotic twins was ascertained through the Colorado Twin Registry containing records available for all twin births in Colorado, excluding the few families that explicitly asked not to be contacted. Of the parents approached by telephone, 86% agreed to participate. A payment of $100 was given for participation. The Norwegian sample of 16 pairs of monozygotic and 19 pairs of same-sex dizygotic twins was ascertained through the Norwegian Medical Birth Registry. All parents in the southwest region of Norway were approached by mail and 58% agreed to participate. No payment was given for participation.

MEASURES

The testing took place over five days, and all five testing sessions were completed within a two-week period. We describe the measures below in sequence according to the testing day and order of administration within each day. Because of space limitations in this report, we can present only brief descriptions of the tests. In cases of commercially available tests, we simply name the test for the most part. In cases where the measures have been created specifically for this project, we provide a brief description and invite readers to contact us for fuller details.

DAY 1

Word Blending. Made available by Lonigan (personal communication, 2000), this test asks children to blend compound nouns such as *baseball* from their components (*base-ball*).

Syllable and Phoneme Blending. Also from Lonigan (personal communication, 2000), children are asked to blend syllables such as *sis-ter*, phonemes and syllables such as *t-oy*, and phonemes such as *m-o-p*.

Sound Matching. From the *Comprehensive Test of Phonological Processing* (Wagner, Torgesen, & Rashotte, 1999), a measure of the ability to recognize shared initial phonemes (e.g., *neck* and *nut*) and shared final phonemes (e.g., *cap* and *lip*).

Nonverbal Intelligence. The Block Design subtest from the *Wechsler Preschool and Primary Scale of Intelligence-Revised* (Wechsler, 1989).

Environmental Print. Children are presented with six commonly seen signs and asked to say the word(s). Examples include *exit* and *McDonalds*.

Word Recognition. The Word Identification subtest from the *Woodcock Reading Mastery Test-Revised* (Woodcock, 1987).

DAY 2

Visuospatial Learning. The Visual Learning subtest from the *Wide Range Assessment of Memory and Learning* (Adams & Sheslow, 1990).

Word Elision. From Lonigan (personal communication, 2000), this test asks children to delete elements of compound nouns such as *boy* from *cowboy* and say what is left.

Syllable and Phoneme Elision. Also from Lonigan (personal communication, 2000), children are asked to delete syllables such as *ger* from *tiger*, and phonemes such as *h* from *hear*.

Letter-phoneme Recognition. In a forced-choice format, children are asked to point to the letter, from a line of four, which corresponds to a spoken phoneme.

Rhyme and Final Phoneme Matching. Ten items are dedicated to recognizing rhyme (e.g., that *peep* rhymes with *sheep*, not *truck* or *frog*), and six to final phoneme identity (e.g., that *bat* ends the same as *kite*, not *mail* or *sock*).

Phoneme Identity Training: Initial /s/. A four-stage teaching routine designed to inculcate the idea that different words can begin with the same phoneme, /s/. Within each stage there are six trials. In each trial, the child is invited to indicate which of three pictures has a name (e.g., *seal*, *dog*, *mop*) that begins with the same sound as the pictured target (*sun* in the first three training stages and *snake* in the fourth).

The stages are characterised by increasing instructional support for the child, and teaching ceases if a child responds correctly to six out of eight consecutive trials. In Stage 1, the child is told to listen to the way *sun* starts and then to indicate which of the three other words starts the same. Feedback is provided simply by affirming that *sun* and, for example, *seal* start the same, or by pointing out that *seal* should be the answer because it starts the same as *sun*. In Stage 2, articulation is added with the child being asked to say all of the words. In Stage 3, the additional element is provided by the trainer stressing the /s/ while pronouncing *sun* and the correct response (the latter during feedback). In Stage 4, in addition to the previous elements, the child is asked to say the target word with the stressed /s/ and, in addition, to articulate the /s/ by itself. The fact that the target (in this case, *snake*) starts with /s/ is pointed out explicitly.

DAY 3

Story Learning. The Story Memory subtest from the *Wide Range Assessment of Memory and Learning* (Adams & Sheslow, 1990).

Rapid Naming. The Rapid Object Naming and Rapid Color Naming subtests from the *Comprehensive Test of Phonological Processing* (Wagner, Torgesen, & Rashotte, 1999).

Confrontation Naming. The Hundred Pictures Naming Test (Fisher & Glenister, 1992).

Letter Name Recognition. As for the letter-phoneme test (above), in a forced-choice format, children are asked to point to the letter, from a line of four, which corresponds to a spoken letter name.

Phoneme Identity Training: Initial /p/. The four-stage phoneme identity teaching routine, which on this occasion teaches the phoneme /p/ in initial position as in *pig*.

DAY 4

Auditory-visual Paired-associate Learning. The Sound Symbol subtest from the *Wide Range Assessment of Memory and Learning* (Adams & Sheslow, 1990).

Print Conventions. The Concepts About Print Test (Clay, 1975). A measure of how familiar children are with aspects of printed language such as the difference between words and pictures, the direction of print, upper and lower case, and the like.

Productive Grammar. The Grammatic Closure subtest from the *Illinois Test of Psycholinguistic Abilities* (McCarthy & Kirk, 1961).

Phoneme Identity Training: Terminal /l/. The four-stage phoneme identity teaching routine, which on this occasion teaches the phoneme /l/ in terminal position as in *bell*.

DAY 5

Vocabulary. The Vocabulary subtest from the *Wechsler Preschool and Primary Scale of Intelligence-Revised* (Wechsler, 1989).

Verbal Working Memory. The Sentence Memory subtest from the *Wechsler Preschool and Primary Scale of Intelligence-Revised* (Wechsler, 1989).

Productive Morphology. A test based on Berko (1958) as adapted by Bradley (personal communication, 1999) and further adapted. The child is asked to complete sentences assessing control over suffixes for plurals, agentives, comparatives, and tense/aspect. The items use nonwords to guard against reliance on memorized forms.

Nonword Repetition. The Children's Test of Nonword Repetition-Revised (Gathercole & Baddeley, 1996).

Phoneme Identity Training: Terminal /t/. The four-stage phoneme identity teaching routine, which on this occasion teaches the phoneme /t/ in terminal position as in *cat*.

PROCEDURE

The children were tested in their homes and/or preschools, generally on five days over a one- or two-week period. Members of each pair were tested at the same time by different experimenters. The test sessions were interspersed with rewards in the form of stickers and with stories read from suitable picture books. In most cases, zygosity was determined from DNA collected through cheek swabs or, in the few cases where this was not possible, from observation and structured questions (Nichols & Bilbro, 1966).

RESULTS AND DISCUSSION

In this brief report, we will consider two main levels of analysis for the preschool data from the cognitive performance measures. First, we will compare the means and standard deviations for each measure in Australia, Norway, and the United States. Second, we will present preliminary analyses of the MZ and DZ correlations and covariances for each measure in a combined sample from Australia and the U.S., and consider the current implications of these correlations and covariances for genetic, shared environment, and nonshared environment influences across the different measures.

The uneven numbers across the measures, evident in some of our tables, are due to two sources. Occasionally, a child was unable to complete a test because of distraction, inattention, or discomfort, in which case both members of a twin pair are lost to analyses based on correlations and covariances. More substantially, we undertook a reevaluation of our methods after we had tested the first 31 pairs of twins, checking for floor and ceiling effects, among other things. We added several measures at this stage including letter-phoneme knowledge, grammatic closure, and visual learning, and we changed the format of some of the static phonological awareness measures.

PERFORMANCE MEANS FOR AUSTRALIA, THE U.S., AND NORWAY

Means and standard deviations (SD) are presented for all measures in table I. The measures are grouped into categories of Phonological Analysis and Synthesis, Phoneme Identity Training, Print Knowledge, Spoken Language Processes, Learning/ Memory, and Nonverbal IQ. One-way analyses of variance and

TABLE I. Variable Means and Standard Deviations for Australia, the U.S., and Norway.

Variable		Au. Mean/(SD)	U.S. Mean/(SD)	Nor. Mean/(SD)
Phonological Analysis & Synthesis				
Word Blending (/12)		8.6 (3.3)	8.8 (3.1)	9.6 (2.6)
Syllable and Phoneme Blending (/12) #		6.4 (2.8)	6.2 (2.4)	7.1 (3.3)
Sound Matching (/20)	~ @	5.5 (4.2)	3.6 (3.1)	3.4 (3.9)
Word Elision (/12)	~	8.0 (3.1)	6.7 (3.0)	7.1 (2.8)
Syllable and Phoneme Elision (/12)	~	4.7 (2.3)	3.9 (1.9)	4.0 (1.7)
Rhyme & Final Phoneme match	~ #	9.4 (3.2)	8.4 (3.0)	9.5 (3.5)
Phoneme Identity Training				
Phoneme Identity Training Initial /s/	*	74.1 (24.0)	63.6 (22.7)	55.5 (23.5)
Phoneme Identity Training Initial /p/	*	70.3 (27.0)	61.5 (26.0)	52.9 (26.2)
Phoneme Identity Training Terminal /l/	~@	59.3 (23.4)	51.3 (20.3)	50.0 (19.8)
Phoneme Identity Training Terminal /t/		60.3 (22.4)	56.6 (22.4)	59.8 (23.2)
Learning/Memory				
Visuospatial Learning (/48)	*	22.5 (8.0)	20.0 (7.8)	16.6 (9.0)
Story Learning Immediate (/55)	@	8.2 (5.4)	7.6 (5.9)	6.2 (6.3)
Auditory-Visual Learning	~	7.0 (4.1)	5.3 (4.4)	5.7 (5.1)
Spoken Language Processes				
Confrontation Naming	*	84.6 (7.5)	75.7 (9.2)	79.7 (9.0)
Vocabulary Scaled	~@	12.2 (3.7)	10.6 (3.1)	10.7 (2.8)
Verbal Working Memory Scaled	@ #	10.9 (2.8)	10.3 (2.8)	6.6 (2.5)
Nonword Repetition (/28)		14.7 (6.0)	13.7 (5.5)	14.3 (5.4)
Rapid Naming Objects Sec.	~	119.9 (46.8)	130.9 (41.8)	126.8 (32.3)

Variable		Au. Mean/(SD)	U.S. Mean/(SD)	Nor. Mean/(SD)
Rapid Naming Colors Sec.		139.8 (50.2)	145.3 (51.0)	152.1 (42.7)
Productive Morphology (/22)		12.6 (5.1)	11.4 (5.0)	10.9 (5.2)
Productive Grammar (/33)	~ #	16.3 (5.4)	13.3 (4.5)	17.2 (5.8)
Print Knowledge				
Environmental Print (/6)	*	3.4 (1.4)	2.5 (1.2)	1.5 (1.2)
Word Recognition	~ @	2.5 (8.6)	0.6 (2.9)	0.0 (0.12)
Letter Name Recognition (/26)	*	18.7 (6.3)	16.8 (6.5)	9.9 (4.7)
Letter-Phoneme Recognition (/26)	~ @	15.0 (6.5)	11.9 (5.9)	10.5 (5.2)
Print Conventions (/24)	~ @	9.8 (4.0)	7.3 (3.8)	6.4 (4.0)
Nonverbal IQ				
WPPSI Block Design Scaled	~ @	11.5 (2.8)	10.3 (2.4)	9.7 (3.6)

Note: * = $p < .05$ for differences among all 3 countries, ~ for differences between Australia and the U.S., @ between Australia and Norway, and # between the U.S. and Norway.

Tukey HSD post hoc tests were performed to test the significance of the differences between countries for each measure. It is apparent that there are many significant differences between the means, with higher scores for the Australian twins over the U.S. and Norwegian twins, in most cases.

The reasons for the generally superior performance of the Australian twins are not clear at this point. It appears that the parents in the Australian families have a similar level of schooling in years compared to the U.S. families, although admission to higher education in Australia is more selective than in the United States. There may have been a selection bias toward more educationally involved families in Australia since almost all had voluntarily affiliated with the twin registry for research. One possibility that we are inclined to reject is differences in test administration. Great effort has been expended to equate testing procedures through several meetings between the Australian and U.S. testers, and the continued sharing of testing procedure videotapes. Moreover, there are group differences in basic measures of print knowledge including letter name, letter sound, printed word knowledge, and concepts about print that are unlikely to be influenced by minor differences in testing procedure.

The differences between Australian and U.S. twins in the basic print-knowledge measures may have influenced their differences in performance on the static and dynamic (learning) measures of phoneme awareness. Based on studies of phoneme awareness in adult illiterates prior to and after learning to read, we know that learning to read increases phoneme awareness (Morais, Cary, Alegria, & Bertelson, 1979). Similarly, the Australian twins' greater early knowledge of print may have resulted in their significantly higher performance in the phoneme learning tasks and several static measures of phoneme awareness.

For the smaller sample of older Norwegian twins, the pattern of group differences with Australia and the U.S. is more variable across measures. In spite of being slightly older, the Norwegian twins clearly had the lowest levels of letter name and printed word knowledge. Their letter-sound knowledge and concepts about print were also lower than for the U.S. twins, but not significantly so. This may reflect the dominant educational view in Norway and in other countries such as Austria that the time for print instruction is in the first grade (starting at age seven) when all children are taught to read. In spite of the Norwegian twins' lower print knowledge, they did achieve an average level of performance in two of the phoneme learning tasks that was similar to that of the U.S. twins, and they were equal to or better than the U.S. twins in the measures of Phonological Analysis and Synthesis.

ESTIMATES OF GENETIC AND ENVIRONMENTAL INFLUENCE FROM MZ AND DZ TWIN CORRELATIONS AND MODELLING OF TWIN COVARIANCES

The Australian and U.S. data were separately standardized within each country prior to combining the data sets and partialling on age to obtain intraclass correlations for MZ and DZ twins. We do not present separate twin correlations for the U.S. and Australian samples because the 27-pair Australian DZ twin sample is still rather small for reliable correlations and heritability estimates. The Norwegian twin sample was not included in these analyses because it is still too small for reliable standardization within that country.

Table II includes the age-partialed MZ and DZ intraclass correlations for the combined Australian and U.S. twins. In ad-

TABLE II. Twin Correlations and Mx Model Fitting Estimates for Individual Measures.

Variable	MZ *r*	DZ *r*	h^2	c^2	e^2
Phonological Analysis & Synthesis					
Word Blending	.28	.07	.28	.00	.72
Syllable and Phoneme Blending	.49	.25	*.53	.00	.47
Sound Matching	.45	.25	.37	.08	.55
Word Elision	.55	.28	.43	.10	.48
Syllable and Phoneme Elision	.26	.22	.05	.21	.74
Rhyme & Final Phoneme match	.50	.27	*.49	.02	.49
Phoneme Identity Training					
Phoneme Identity Training Initial /s/	.48	.47	.09	*.41	.50
Phoneme Identity Training Initial /p/	.60	.33	**.56	.06	.38
Phoneme Identity Training Terminal /l/	.33	.27	.18	.17	.64
Phoneme Identity Training Terminal /t/	.51	.39	.36	.19	.45
Learning/Memory					
Visuospatial Learning	.51	.18	*.47	.00	.53
Story Learning Immediate	.45	.18	**.46	.00	.54
Auditory-Visual Learning	.48	.08	**.45	.00	.55
Spoken Language Processes					
Confrontation Naming	.68	.71	.00	***.70	.30
Vocabulary Scaled	.47	.33	.20	.26	.54
Verbal Working Memory Scaled	.68	.40	***.61	.09	.30
Nonword Repetition	.39	.33	.19	.22	.59
Rapid Naming Objects Sec.	.25	.33	.00	*.30	.70
Rapid Naming Colors Sec.	.54	.32	***.66	.00	.34
Productive Morphology	.58	.42	.31	.27	.42
Productive Grammar	.59	.53	.06	**.53	.41

Table II (continued)

Variable	MZ r	DZ r	h^2	c^2	e^2
Print Knowledge					
Environmental Print	.63	.52	.24	**.41	.35
Word Recognition	.91	.35	—	—	—
Letter Name Recognition	.78	.69	.19	***.60	.21
Letter-Phoneme Recognition	.67	.66	.11	***.59	.30
Print Conventions	.46	.47	.02	**.45	.53
Nonverbal IQ					
WPPSI Block Design Scaled	.50	.27	*.50	.02	.47

Note: * = $p < .05$; ** = $p < .01$; *** = $p < .001$.

dition, maximum likelihood estimates (Neale & Cardon, 1992) of proportional influences from genes (broad heritability is h^2), from shared environment (c^2), and from nonshared environment (e^2) obtained from within-pair covariances using the Mx statistical modelling package (Neale, 1999) are presented in table II.

Heritability can be roughly estimated in a straightforward way by doubling the difference between the MZ and DZ correlations, because DZ twins share half their segregating genes on average. Heritability should not be higher than the MZ correlation, so the MZ correlation can be used as an upper-bound estimate of heritability, if doubling the MZ-DZ difference would yield a higher estimate. Nonshared environment (e^2), including test error, can be estimated from the difference between 1 and the MZ correlation. Finally, shared environment can be estimated from $1 - (h^2 + e^2)$.

The Mx model fitting estimates in table II vary slightly from those obtained from the correlations, but with this small sample, the confidence intervals are fairly broad and the estimates based on the two different methods are not significantly different. The Mx models have the advantage of providing separate chi-square tests of significance for the contributions of genes (h^2) and shared environment (c^2). The results of these significance tests are indicated in the last two columns of table II.

Table III includes Mx modelling results for six composite measures based on adding their individual measures' age adjusted z scores. The results for each composite measure and the respective individual measures are discussed below under headings that correspond to the measurement categories in tables I and II.

TABLE III. Twin Correlations and Mx Model Fitting Estimates for Composite Measures.

Measure	MZ r	DZ r	h^2	c^2	e^2
Phonological Analysis & Synthesis	.69	.40	.52**	.16	.31
Phoneme Identity Training	.69	.48	.50***	.22	.28
Learning/Memory	.49	.18	.47*	.00	.53
Grammar/Morphology	.67	.51	.22	.43*	.35
Vocabulary	.69	.55	.18	.49**	.33
Print Knowledge	.83	.68	.28*	.55**	.17

Note: Sample sizes ranged between 80-109 MZ pairs and 83-103 DZ pairs. * = $p < .05$; ** = $p < .01$; *** = $p < .001$ for the significance of the estimates for heritiability (h^2) and shared environment (c^2) greater than 0.

RESULTS OF PHONOLOGICAL ANALYSIS AND SYNTHESIS

Heritabilities for individual differences in the six static measures of Phonological Analysis and Synthesis in table II ranged from .05 for Syllable and Phoneme Elision to .53 for Syllable and Phoneme Blending, with a mean of .36 across all measures in this category. The average shared environment estimate was .07 and the average nonshared environment estimate was .58. The high nonshared environment estimates across the individual tests certainly include measurement error associated with the limited number of trials in each test and variability in the young twins' attention to the tasks. In addition, static measures of phoneme-level awareness tended to have floor effects for these young twins.

The Phonological Analysis and Synthesis composite measure in table III combined assessments across several levels of phonological segmentation and blending (future analyses with larger samples will separate children's skills in each of these levels). The advantage of the composite measure for our present analyses is that it includes a large number of trials across six testing situations. This likely reduced the contribution of measurement error variance and floor effects to the estimate of nonshared environment (e^2 = .31), and it increased the significant estimate of genetic influence (h^2 = .52) compared to the averages for the individual static measures. Shared environment influence for the composite measure (c^2 = .16) could be dropped from the model without a significant loss of fit.

RESULTS OF PHONEME IDENTITY TRAINING

Heritability estimates for the four Phoneme Identity Training sessions ranged from .09 for initial /s/ to .56 for initial /p/, with an average of .30. The average shared environment estimate was .21, and the average nonshared environment estimate was .49. The Phoneme Identity Training composite measure yielded a lower estimate of nonshared environment (e^2 = .28) and a higher estimate of genetic influence (h^2 = .50) compared to the average for the individual measures. As for the static Phonological Analysis and Synthesis composite, heritability for the Phoneme Identity Training composite was highly significant, but shared environment (c^2 = .22) could be dropped from the model without a significant loss of fit.

RESULTS OF MEASURES OF LEARNING AND MEMORY

Heritability estimates in table II for the three visual and verbal learning/memory tasks (Visuospatial Learning, Story Learning, and Auditory-Visual Learning) were similar, with an average of .46. The average shared environment estimate was .0, and the average nonshared environment estimate was .54. The composite measure in table III yielded a significant heritability of .47, and shared environment (c^2 = .0) could be dropped from the model without a significant loss of fit. The pattern of significant genetic and nonsignificant shared environment influence was similar to that for the Phonological Analysis and Synthesis and Phoneme Identity Training composites.

RESULTS OF SPOKEN LANGUAGE PROCESSES

The estimates of genetic and environmental influence in table II varied widely across the different measures in this broad category. Rapid Naming Objects showed no genetic influence and very high nonshared environment, suggesting poor reliability, while significant genetic influence was found for Rapid Naming Colors. Nonword Repetition showed no significant genetic influence and high nonshared environment. Verbal Working Memory showed significant genetic influence and little evidence for shared environment. A much larger sample will be needed for sufficient power to test for differences in results across these measures.

We grouped the remaining measures in the broad Spoken Language Processes category into two different composite scores. The first composite combined the scores from the Productive Morphology and Productive Grammar measures, labelled Grammar/Morphology in table III. The second composite combined the scores from Confrontation Naming and Vocabulary Scaled (from the *WPPSI*), labelled Vocabulary in table III. In contrast to the composite results described previously, these two language composites did not show statistically significant heritability, but they did show significant shared environment influences.

In Stromswold's (2001) review of the heritability of language, results have generally supported the existence of genetic effects on aspects of syntactic and morphological processes in children, although methods of assessment have varied widely and sample sizes have often been small, resulting in a mixed picture. For example, Mather and Black (1984) found a very high shared environment effect alongside a small genetic effect for a morphological test very much like ours, while Fischer (1973) reported no genetic effect for this process. Mather and Black also identified substantial heritability in the test of productive grammar that we also employed, at odds with our finding, although their sample of 50 MZ twins and 29 DZ twins was less than half the size of ours.

The Vocabulary results are also partially at odds with the general observation from other twin studies that there is reliable heritability for vocabulary size across the age range 14 months to 13 years (Stromswold, 2001). However, they are consistent with aspects of these other twin studies. For instance, not all studies have found MZ correlations to be reliably higher than DZ correlations for vocabulary, even in older children (e.g., Foch & Plomin, 1980), and Stomswold's metaanalysis showed shared environment effects of .66 compared to genetic effects of .29 in the youngest twins. Stromswold concludes that "as children get older, heritable factors and nonshared environment factors play an increasing role in spoken vocabulary, and shared environment factors play a decreasing role" (pp. 670–671). It remains to be seen whether our sample will show this developmental trend. It also remains to be seen whether the h^2 values for the two spoken language composites—.22 for Grammar/Morphology and .18 for Vocabulary—remain nonsignificant with a larger sample.

RESULTS OF PRINT KNOWLEDGE

Similar to the two composite language measures, there was little genetic influence and strong shared environment influence on individual differences in measures of Print Knowledge, excluding Word Recognition. The high MZ and lower DZ correlations shown for Word Recognition in table II are due to the presence of a few extreme outliers who read a large number of words. When the correlations were recomputed after excluding the 10% of subjects who read more than three words, the MZ correlation was .39 and the DZ correlation was .50. The modal score for Word Recognition was 0% correct for 83% of the subjects. Therefore, we did not model the data on Word Recognition to estimate heritability since the distribution for the full sample was badly skewed, and the distribution without the outliers had severely restricted range.

The four adequately distributed measures under Print Knowledge in table II are Environmental Print (h^2 = .24, c^2 = .41, e^2 = .35), Letter Phoneme Recognition (h^2 = .11, c^2 = .59, e^2 = .30), Letter Name Recognition (h^2 = .19, c^2 = .60, e^2 = .21), and Print Conventions (h^2 = .02, c^2 = .45, e^2 = .53). The results are quite striking and remarkably consistent across these four measures of Print Knowledge: there were no significant genetic influences but strong shared environment influences. The results for the Environmental Print, Letter Name Recognition, Letter Phoneme Recognition, and Print Conventions composite measure shown in table III revealed a modest but significant heritability (h^2 = .28), and a stronger influence from shared environment (c^2 = .55). Large shared environment effects on print awareness may reflect a very high degree of diversity in the home and preschool conditions that support or fail to support this knowledge, and this can be explored further as we incorporate our environmental measures in future analyses.

Letter knowledge and phonological skills are correlated, even in preschool children. For instance, the correlation between Letter Name Recognition and Sound Matching (the only phonological test with purely phoneme-level items) in our sample was .35, and between Letter Phoneme Recognition and Sound Matching was .45. In a sample of 128 preschool children reported on in Byrne and Fielding-Barnsley (1991), letter-name knowledge and a test of phoneme identity also correlated .45. Hence, there is an apparent paradox in the fact that letter knowledge shows high shared environment effects and no genetic effects, whereas correlated phonological processing skills show the reverse etiological pattern. We are not in a position to account for this situation with any certainty, but possibilities exist that will be worth further exploration. For example, if we accept that our samples' variation in letter knowledge is largely an outcome of home and preschool environments, and if we further accept that letter knowledge can provide a platform for insights into phonemic structure (cf. Morais et al., 1979), then genetic endowment might determine how effectively a child can use that platform for developing phonological awareness.

Although the present estimates of shared environment influence for Phonological Analysis and Synthesis (c^2= .16) and

Phoneme Identity Training (c^2= .22) are not significantly greater than 0 in this small sample, we certainly do not want to argue that there is no shared environment influence on phonological skills in preschool twins. A larger sample may reveal significant influences from shared environment that are associated with shared environment influences on letter knowledge. Differences associated with letter knowledge may raise or lower the average level of the twins' phonological skills, perhaps contributing to the nonsignificant shared environment estimates. However, in the present sample, genetic influences appear to be more important than shared environment influences on individual differences in preschool phonological skills.

CONCLUSIONS AND FUTURE GOALS

The three main findings from our preliminary behavior-genetic analyses are the following. First, to our knowledge, the present analyses provide the first evidence for reliable genetic influences on individual differences in phonological awareness among preschool twins. This result is consistent with the substantial genetic influence on phoneme awareness that is found for group deficits and individual differences across the normal range in school-age children between 8 and 18 years of age (Gayán & Olson, 2001; Gayán & Olson, under review; Olson, Wise, Conners, Rack, & Fulker, 1989). The school-age twin studies also show strong genetic correlations between phoneme awareness and phonological word-reading skills (i.e., both are influenced by the same genes). The latter result suggests but does not prove a causal link from phoneme awareness to reading, because there is a reciprocal relation between growth in word reading and phoneme awareness (Morais et al., 1979).

The second main finding is the identification of significant genetic influences (and negligible shared environment influence) on learning and memory processes in preschoolers. The processes are as varied as verbal working memory (the *WPPSI* Sentence Memory subtest), longer-term memory for verbal, symbolic, and visuospatial information (the Story Memory, Sound-Symbol, and Visual Learning subtests of the *WRAML*), and acquisition of phonemic awareness (the specially created training in phoneme identity). It remains to be seen how much these variables share common psychological and genetic ground, and how they relate to later growth in reading.

To address the causal role of phoneme awareness and learning processes through both genetic and environmental paths to individual differences in reading development, we plan to test the twins' phonological and reading skills at the end of kindergarten, first grade, and second grade. Developmental behavior-genetic analyses will show how genetic, shared environment, and nonshared environmental influences on different types of phonological awareness (i.e., awareness of phonemes versus larger units, segmentation versus blending versus identity detection) and on different types of learning processes (i.e., short- versus long-term, verbal versus visuospatial, phonology-specific versus more general) in preschool twins are related to the twins' subsequent development in phonological skills and different measures of reading and spelling. We will also be attending to the genetic and environmental pathways from preschool language, rapid naming, and nonword repetition measures to later reading development.

The third main finding is that in sharp contrast to the significant genetic and nonsignificant shared environment influences for phonological skills and Learning/Memory measures, Print Knowledge (particularly Letter Name Recognition) and Vocabulary (particularly Confrontation Naming) measures showed little or no heritability, and consistently strong influence from shared environment. Only the Print Knowledge composite measure showed a modest but statistically significant influence from genes. Young children's print knowledge, particularly letter-name knowledge, has long been cited as the most reliable predictor of later reading development (cf. Adams, 1990). The second most powerful predictor has been vocabulary, particularly confrontation naming (Byrne, Fielding-Barnsley, Ashley, & Larsen, 1997; Scarborough, 1998). It will be interesting to see if shared environment effects on the twins' subsequent reading skills in the first and second grades are linked to their preschool Print Knowledge and Vocabulary scores.

ACKNOWLEDGEMENTS

This research is being conducted with the support of Australian Research Council grant A79906201, National Institutes of Health grants 2 P50 HD27802 and 1 R01 HD38526, and a Norwegian grant from Stavanger College. We are grateful to the many twins and their families who have participated in the research, and for the expert assistance of our project coordinators and testers in the United States (Kim Corley, Rachael Cole, Barb Elliott, Kari Gilmore, and Angela Villella), in Australia (Fiona

Black, Nicole Church, Marreta Coleman, and Annette Stevenson), and in Norway (Charlotte Gjerde and Trine Tengesdal). We also thank our consultants, Chris Lonigan and Rick Wagner, for their advice and contribution of several static measures of phonological awareness.

Address correspondence to: Brian Byrne (bbyrne@metz.une. edu.au) or Richard Olson (rolson@psych.colorado.edu).

References

Adams, M. J. (1990). *Beginning to read: Thinking and learning about print.* Cambridge, MA: MIT Press.

Adams, W., & Sheslow, D. (1990). *Wide range assessment of memory and learning.* Wilmington, DE: Jastak Associates.

Berko, J. (1958). The child's learning of English morphology. *Word*, *14*, 47–56.

Boada, R., Willcutt, E. G., Tunick, R. A., Chhabildas, N. A., Olson, R. K., DeFries, J. C., & Pennington, B. F. (in press). A twin study of the etiology of high reading ability. *Reading and Writing: An Interdisciplinary Journal.*

Bradley, D. (1999). Personal communication.

Bradley, L., & Bryant, P. E. (1983). Categorising sounds and learning to read—A causal connection. *Nature, 301*, 419–421.

Byrne, B. (1998). *The foundation of literacy: The child's acquisition of the alphabetic principle.* Hove, UK: Psychology Press.

Byrne, B., & Fielding-Barnsley, R. (1989). Phonemic awareness and letter knowledge in the child's acquisition of the alphabetic principle. *Journal of Educational Psychology*, *81*, 313–321.

Byrne, B., & Fielding-Barnsley, R. (1990). Acquiring the alphabetic principle: A case for teaching recognition of phoneme identity. *Journal of Educational Psychology, 82*, 805–812.

Byrne, B., & Fielding-Barnsley, R. (1991). Evaluation of a program to teach phonemic awareness to young children. *Journal of Educational Psychology, 83*, 451–455.

Byrne, B., Fielding-Barnsley, R., & Ashley, L. (2000). Effects of preschool phoneme identity training after six years: Outcome level distinguished from rate of response. *Journal of Educational Psychology, 92*, 659–667.

Byrne, B., Fielding-Barnsley, R., Ashley, L., & Larsen, K. (1997). Assessing the child's and the environment's contribution to reading acquisition: What we know and what we don't know. In B. Blachman (Ed.), *Foundations of reading acquisition and dyslexia: Implications for early intervention* (pp. 265–285). Mahwah, NJ: Lawrence Erlbaum Associates.

Carlisle, J. F. (1987). The use of morphological knowledge in spelling derived forms by learning-disabled and normal students. *Annals of Dyslexia, 27*, 90–108.

Catts, H. W. (1989). Speech production deficits in developmental dyslexia. *Journal of Speech and Hearing Disorders, 54*, 422–428.

Catts, H. W. (1993). The relationship between speech-language impairments and reading disabilities. *Journal of Speech and Hearing Research*, *36*, 948–958.

Clay, M. (1975). *The early detection of reading difficulties: A diagnostic survey.* Auckland, New Zealand: Heinemann.

Davis, C. J., Knopik, V. S., Olson, R. K., Wadsworth, S. J., & DeFries, J. C. (2001). Genetic and environmental influences on rapid naming and reading ability: A twin study. *Annals of Dyslexia, 51*, 241258.

DeFries, J. C., & Alarcon, M. (1996). Genetics of specific reading disability. *Mental Retardation and Developmental Dissabilities Research Reviews, 2*, 3947.

DeFries, J. C., Alarcon, M., & Olson, R. K. (1997). Genetics and dyslexia: Developmental differences in the etiologies of reading and spelling deficits. In C. Hulme & M. Snowling (Eds.), *Dyslexia: Biological bases, identification, & intervention* (pp. 20–37). London: Whurr Publishing.

Elbro, C., Borstrøm, I., & Petersen, D. K. (1998). Predicting dyslexia from kindergarten: The importance of distinctness of phonological representations of lexical items. *Reading Research Quarterly, 33*, 36–60.

Fischer, K. M. (1973). *A comparison of the similarities in language skills of identical and fraternal twins.* Unpublished doctoral dissertation. University of Pennsylvania, Philadelphia.

Fisher, S. E., Francks, C., Marlow, A. J., MacPhie, L., Williams, D. F., Cardon, L. R., Ishikawa-Brush, Y., Talcott, J. B., Richardson, A. J., Gayán, J., Olson, R. K., Pennington, B. F., Smith, S. D., DeFries, J. C., Stein, J. F., & Monaco, A. P. (2002). Genome-wide scans in independent samples reveal strong convergent evidence for a chromosome 18 quantitative-trait locus influencing developmental dyslexia. *Nature Genetics, 30*, 86–91.

Fisher, J. P., & Glenister, J. M. (1992). *The hundred pictures naming test*. Hawthorn, Australia: Australian Council for Educational Research.

Foch, T. T., & Plomin, R. (1980). Specific cognitive abilities in 5- to 12-year-old twins. *Behavior Genetics, 10*, 507–520.

Gallagher, A., Frith, U., & Snowling, M. J. (2000). Precursors of literacy delay among children at genetic risk for dyslexia. *Journal of Child Psychology and Psychiatry, 41*, 203–213.

Gathercole, S. E., & Adams, A. (1993). Phonological working memory in very young children. *Developmental Psychology, 29*, 770–778.

Gathercole, S., & Baddeley, A. (1989). Evaluation of the role of phonological STM in the development of vocabulary in children: A longitudinal study. *Journal of Memory and Language, 28*, 200–213

Gathercole, S., & Baddeley, A, (1996). *The children's test of nonword repetition-revised.* New York: Harcourt.

Gayán, J., & Olson, R. K. (2001). Genetic and environmental influences on orthographic and phonological skills in children with reading disabilities. *Developmental Neuropsychology, 20*(2), 487–511.

Gayán, J., & Olson, R.K. (under review). Genetic and environmental influences in individual differences in printed word recognition.

Gayán, J., Smith, S. D., Cherny, S. S., Cardon, L. R., Fulker, D. W., Kimberling, W. J., Olson, R. K., Pennington, B., & DeFries, J. C. (1999). Large quantitative trait locus for specific language and reading deficits in chromosome 6p. *American Journal of Human Genetics, 64*, 157–164.

Grigorenko, E. L., & Sternberg, R. J. (1998). Dynamic Testing. *Psychological Bulletin, 124*, 75–111.

Hindson, B. A. (2001). *Linguistic and cognitive characteristics of preschool children at risk for reading disability.* Unpublished doctoral dissertation. University of New England, Armidale, NSW, Australia.

Lonigan, C. R. (2000). Personal communication.

Lyytinen, H. (1997). In search of the precursors of dyslexia: A prospective study of children at risk for reading problems. In C. Hulme & M. Snowling (Eds.), *Dyslexia: Biology, cognition and intervention* (pp. 97–107). London: Whurr.

Man, J. (2000). *Alpha beta : How 26 letters shaped the western world.* New York: John Wiley.

Mather, P. L., & Black, K. N. (1984). Hereditary and environmental influences on preschool twins' language skills. *Developmental Psychology, 20*, 303–308.

McCarthy, J. J., & Kirk, S. A. (1961). *The Illinois test of psycholinguistic abilities.* Urbana, IL: University of Illinois Press.

Morais, J., Cary, L., Alegria, J., & Bertelson, P. (1979). Does awareness of speech as a sequence of phonemes arise spontaneously? *Cognition, 7*, 323–331.

Neale, M. C. (1999). *Mx: Statistical modeling (5th ed.).* Richmond, VA: Department of Psychiatry.

Neale, M. C., & Cardon, L. R. (1992). *Methodology for genetic studies of twins and families*, NATO ASI series. Dordrecht, The Netherlands: Kluwer Academic Press.

Nichols, R. C., & Bilbro, W. C., (1966). The diagnosis of twin zygosity. *Acta Genetica, 16*, 265–275.

Olson, R. K., Forsberg, H., & Wise, B. (1994). Genes, environment, and the development of orthographic skills. In V. W. Berninger (Ed.), *The varieties of orthographic knowledge I: Theoretical and developmental issues* (pp. 27–71). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Olson, R. K., Wise, B., Conners, F., Rack, J., & Fulker, D. (1989). Specific deficits in component reading and language skills: Genetic and environmental influences. *Journal of Learning Disabilities*, 22, 339–348.

Pennington, B. F., & Lefly, D. L. (2001). Early reading development in children at family risk for dyslexia. *Child Development, 72*, 816–833.

Sattler, J.M. (1988). *Assessment of children*. San Diego, CA: Jerome M. Sattler, Publisher.

Scarborough, H. S. (1991a). Early syntactic development of dyslexic children. *Annals of Dyslexia, 41*, 207–220.

Scarborough, H. S. (1991b). Antecedents to reading disability: Preschool language development and literacy experiences of children from dyslexic families. *Reading and Writing, 3*, 219–233.

Scarborough, H. S. (1998). Early detection of children at risk for reading disabilities: Phonological awareness and other promising predictors. In B. K. Shapiro, P. J. Accardo, & A. J. Capute (Eds.), *Specific reading disability: A view of the spectrum* (pp. 75–119). Timonium, MD: York Press.

Segal, N. L. (2000). *Entwined Lives: Twins and what they tell us about human behavior.* New York: Plume.

Stromswold, K. (2001). The heritability of language: A review and metaanalysis of twin, adoption, and linkage studies. *Language, 77*, 647–723.

Swanson, H. L., & Siegel, L. (2001). Learning disabilities as a working memory deficit. *Issues in Education, 7*, 1–48.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *The comprehensive test of phonological processes (CTOPP).* Austin, TX: PRO-ED.

Wechsler, D. (1989). *Manual for the Wechsler preschool and primary scale of intelligence-revised.* New York: Psychological Corporation.

Wilcutt, E. G., Pennington, B. F., Smith, S. D., Cardon, L. R., Gay·n, J., Knopic, V. S., Olson, R. K., & DeFries, J. C. (2002). Quantitative trait locus for reading disability on chromosome 6p is pleiotropic for attention-deficit/hyperactivity disorder. *American Journal of Medical Genetics (Neuropsychiatric Genetics), 114*, 260–268.

Wolf, M., & Bowers, P. (1999). The question of naming-speed deficits in developmental reading disabilities: An introduction to the double-deficit hypothesis. *Journal of Educational Psychology, 91*, 1–24.

Woodcock, R. W. (1987). *Woodcock reading mastery tests-revised.* Circle Pines, MN: American Guidance Service.