Published in final edited form as:
Sci Stud Read. 2014 December 31; 18(1): 38–54. doi:10.1080/10888438.2013.800521.

Why do Children Differ in Their Development of Reading and Related Skills?

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Abstract

Modern behavior-genetic studies of twins in the U.S., Australia, Scandinavia, and the U.K. show that genes account for most of the variance in children's reading ability by the end of the first year of formal reading instruction. Strong genetic influence continues across the grades, though the relevant genes vary for reading words and comprehending text, and some of the genetic influence comes through a gene – environment correlation. Strong genetic influences do not diminish the importance of the environment for reading development in the population and for helping struggling readers, but they question setting the same minimal performance criterion for all children.

Why do children differ in their development of reading and related skills? This fundamental question has been addressed in much of the research conducted by members of the Society for the Scientific Study of Reading (SSSR) over the past 20 years. A casual perusal of SSR journal publications since 1997 and SSSR conference presentations since the beginning of the Society in 1993 reveals answers that are predominantly environmental, including preschool language and print exposure, quality and quantity of reading instruction in school, peer and family influences, socioeconomic level, and learning to read in a second language. This environmental focus is understandable from the obvious fact that reading is a learned skill that initially depends on formal instruction. The environmental focus is also supported by many experiments showing significant effects from manipulating the reading environment, and by studies reporting correlations between reading and related skills, such as phonological awareness and phonological decoding. Indeed, these studies are often

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interpreted as implying an environmentally-based causal pathway from phonological skills to the individual differences and deficits observed in reading.

A different perspective on the etiology of individual differences in reading and related skills has been provided by behavior-genetic studies that compare similarities between large samples of identical (monozygotic or MZ) and fraternal (dizygotic or DZ) twin pairs who share their home and school environment, yet differ in their additive genetic similarity (100% for MZ pairs, 50% of segregating genes on average for DZ pairs). This natural experiment is unique in its ability to estimate the average influence on individual differences in reading and related skills that arise from genes, from shared environments that make twins in a pair similar (e.g., books in the home, general family support for reading, shared teachers, classrooms, peers), and from non-shared environments that make twins different (e.g., different peers, teachers, classrooms, illnesses, birth problems, accidents, and measurement error) (Plomin, DeFries, McClearn, & McGuffin, 2008).

In addition to assessing genetic and environmental influences on individual variation in specific reading and related skills, behavior-genetic research can also address genetic and environmental influences on the correlations between different skills, such as between word recognition, listening comprehension, and reading comprehension (cf., Keenan, Betjemann, Wadsworth, DeFries, & Olson, 2006). This knowledge can provide a deeper understanding of why children differ, not only for genetic reasons, but also for reasons related to environmental influences.

Before we explore the results from recent behavior-genetic studies of reading, we need to clarify some important general qualifications and limitations of behavior-genetic research using data from identical and fraternal twins reared together. First, we sometimes hear concerns that our behavior-genetic results might imply a genetic basis for mean differences between racial, ethnic, or regional groups' reading ability. It is important to emphasize that behavior-genetic studies cannot address the etiology of group mean differences. They are assessments of the sources of variance between individuals in a sample, not mean performance of that sample. Thus, environmental differences may completely account for any mean group differences, even when genetic influences explain individual differences within those groups.

Second, it is important to understand that estimates of genetic and environmental influence from twin studies are specific to the behaviorally relevant environmental range in the sampled populations. Twin samples with low environmental variation are likely to yield higher genetic and lower environmental estimates when compared to samples with high environmental variation (see Samuelsson, Olson, & Byrne, 2013, for examples).

Third, behavior-genetic studies only describe the average current balance of genetic and environmental influences on individual differences within a sample. They do not specify the genetic and environmental etiology for any individual in that sample.

Fourth, estimates of genetic and environmental influences from behavior-genetic studies do not speak to the possibility for changing the average reading level in a population by

manipulating the quantity and quality of reading instruction or practice, nor do they speak to the potential benefits of extraordinary environmental interventions for reading disabilities.

Fifth, genes express themselves through the environment. For example, we will present evidence that genes related to reading ability influence the amount of reading practice, resulting in a positive gene – environment correlation. This correlation likely accounts for at least part of our estimates of genetic influence from twin studies. It has important implications for environmental intervention that we will consider in the concluding section.

Regardless of these limitations and qualifications, we will argue that considered together, the results of modern behavior-genetic twin studies of individual differences and deficits in reading provide the best evidence for why, on average, children differ in their reading and related skills. Following a brief overview of the major behavior-genetic studies of reading conducted over the past 20 years, we will turn to what we think are some of the most important results from those studies. In the final section of our review, we will consider the implications of the behavior-genetic results for education and directions for future research.

Overview of Modern Behavior-Genetic Studies of Reading

In 1992, the National Institutes of Health (NIH) began providing substantial funding for twin research focused on the genetic and environmental etiology of learning difficulties in reading (e.g., “dyslexia”), and more recently on ADHD and math deficits, through the Colorado Learning Disabilities Research Center (CLDRC) (DeFries et al. 1997; Olson, 2004; 2006). Beginning around 2000, NIH also began funding longitudinal twin studies of individual differences in pre-reading and early-reading development that are being conducted in Colorado, Florida, and Ohio. The longitudinal studies in the U.S. are complemented by others being conducted in Australia, Scandinavia, and the U.K.. Together, these longitudinal studies provide important cross-language and cross-cultural perspectives on the etiology of individual differences in reading development. Thus, the 20-year history of SSSR commemorated by this special issue largely overlaps with the emergence of modern behavior-genetic studies focused on reading and related skills.

Our goal in this paper is to highlight the most important themes from modern behavior-genetic research on reading and discuss their broader implications. We will concentrate on longitudinal studies of individual differences in unselected population samples, but we will first discuss a few key findings from research on twin pairs wherein at least one member was selected for reading disability.

The Genetic and Environmental Etiology of Reading Disability

Prior to 1985, the limited behavior-genetic research on reading disability used a categorical definition. Evidence for genetic influence was based simply on a comparison of diagnostic concordance rates for MZ and DZ twin pairs (both “dyslexic” or just one member “dyslexic”). Subsequently, DeFries and Fulker (1985) recognized that the continuous normal distribution of reading ability in the population could be used to support a continuous regression method for assessing the average genetic and environmental etiology of twins’ reading disability, based on the similarity of the MZ and DZ cotwins’ regression to the

population mean. This “DF” model yielded more statistically powerful and accurate estimates of genetic and environmental influence on group deficits in reading and related skills.

When the DF model has been applied to study the etiology of reading disability group membership in the CLDRC and an independent study in the U.K., we find broadly similar results. In describing the results, we will follow behavior-genetic convention and label additive genetic influence as A, shared environment influence as C, and non-shared environment influence as E. Together these three influences account for 100% of the total phenotypic variance, so we can express the A, C, and E influences as accounting for percentages of the phenotypic variance. Here and in the rest of the paper, we only report A (genetic) and C (shared environment) percentages, because E (non-shared environment including measurement error) simply equals 100% – (A% + C%). So for example, if A has been estimated at 40% and C has been estimated at 50%, then it can be assumed that E has been estimated at 10%.

Friend, DeFries, & Olson. (2008) applied the DF model to a composite of reading and spelling data from 545 same-sex twin pairs at mean age 11.4 years in which at least one member of each pair scored below the 10^{th} percentile. The average influence on reading-disability group membership in this CLDRC sample was A = 61% for genetic and C = 30% for shared environment. Harlaar, Spinath, Dale, and Plomin (2005) found very similar results in their large and representative population sample of seven-year-old twins tested on a composite of word and nonword reading near the end of first grade in the U.K. (A = 59%, C = 30%). In both the Friend et al. and Harlaar et al. studies, genetic, shared environment, and non-shared environment influences were all statistically significant for reading disability, but the average influence of genes was about twice as strong as the shared environment influence.

Of course we would like to know the specific genetic and environmental etiology for individual children, but behavior-genetic data cannot provide this answer; it only provides information about the average etiology of reading-disability group membership. It is therefore possible that for some individual children within the group with reading disability, environmental factors may have been the major or only influence, while for others, genes may have been the major or only influence. However, it is possible to expand the DF model to ask if the degree of genetic and environmental influences on reading disability is significantly related to individual differences on other variables, thus bringing us closer to an understanding of differential genetic and environmental etiology within the reading disabled group. Friend et al. (2008) did this using parents’ years of education to explore the possibility of a “genetic-influence by environment” interaction. They found that genetic influence was significantly higher on average for children with reading disability who had parents with higher education, compared to children with lower parent education. For children with lower parent education, shared family environment and genes were about equally influential, on average. One interpretation of these results is that children who fail in reading in spite of having highly educated parents (and likely a better environment for learning to read) are more likely to have genetic than environmental constraints on their reading development.

The interaction between parent education and genetic influence on reading has also been explored for high-reading group performance using the same DF model (Friend et al., 2009). Twin pairs with at least one member performing at least one standard deviation above the population mean on the TOWRE word and nonword reading efficiency composite (Torgesen, Wagner, & Rashotte, 1999) were selected from representative population twin samples in Colorado and the U.K. Genetic influence on high reading group membership was substantial (50% - 72%), depending on grade level and country, and the level of genetic influence interacted with parents' education. But interestingly, the pattern for high-level readers was quite different than for low-level readers. For low-level readers, genetic influence was higher with higher parent education; whereas for high-level readers, genetic influence was greater for children with low parent education. In other words, children who read well, in spite of environmental disadvantages that are often associated with low parent education, are more likely to have higher genetic influence on their high performance. Thus, the Friend et al. (2008; 2009) studies show that the balance of genetic and environmental influences on extreme group membership varies depending on the environmental circumstances for children within those groups.

The Genetic and Environmental Etiology of Individual Differences in Reading

While it is important to understand the etiology of reading disabilities because adequate reading is so important for broader educational and professional development, it is also important to understand the etiology of the full normally-distributed variation in reading and related skills in the population. In this section we first provide an overview of some recent results from the CLDRC that have focused on the etiology of individual differences in reading comprehension, language comprehension, word recognition, and their correlation among children between age 8 to 18 years. Then we will turn to results from recent longitudinal twin studies of individual differences in pre-reading and early reading development.

Do the Same Genetic and Environmental Factors Influence Word Recognition, Listening Comprehension, and Reading Comprehension?

Twin research in the CLDRC initially focused primarily on the etiology of deficits and individual differences in word reading, spelling, and related skills such as phonological awareness, phonological decoding, and orthographic coding (DeFries, Fulker & Labuda, 1987; Gayán & Olson, 2001; 2003; Olson, Wise, Conners, Rack, & Fulker, 1989). Beginning in 2000, a component of the CLDRC directed by Jan Keenan at the University of Denver introduced new measures of reading and listening comprehension so we could better understand how genetic and environmental influences on basic word reading skills and language skills influenced comprehension of text, the ultimate goal of reading. Keenan et al. (2006) explored the genetic and environmental basis for the "simple view" of reading comprehension proposed by Hoover and Gough (1990), wherein individual differences in reading comprehension can be accounted for by listening comprehension and word recognition or decoding. Keenan et al. found that the genetic correlation (r_g) between word recognition and listening comprehension was modest (r_g = .37), and that in accord with the

simple view, these two skills accounted for all of the significant genetic influences on reading comprehension. Subsequent analyses using an expanded sample from the CLDRC confirmed these basic results (Betjemann, Keenan, Olson, & DeFries, 2011), and so has a recent study by Harlaar et al. (2010) based on twin data from Ohio. In contrast, shared environmental influences were highly correlated across word recognition, listening comprehension, and reading comprehension in these studies. Thus, it is the largely independent genetic influences on listening comprehension and word recognition that account for their unique contributions to individual differences in reading comprehension.

The research on reading comprehension in the CLDRC has raised questions about how different methods of assessing reading comprehension vary in their relations to word recognition and listening comprehension. In essence, the genetic correlations of reading comprehension with word reading and listening comprehension differ dramatically between decoding-dependent and listening-dependent measures of reading comprehension (Betjemann et al., 2011; Keenan, Betjemann and Olson, 2008). Thus, different tests used to measure the same construct may manifest very different patterns of genetic covariation.

Converging evidence on the differential etiology of printed word recognition and oral language has come from our International longitudinal Twin Study (ILTS). Olson et al. (2011) found that at the end of 4^{th} grade, oral language comprehension (a vocabulary latent trait) and word decoding latent traits had significant independent genetic influences, and together they accounted for all of the high genetic influence (A = 86%, C = 9%) on a reading-comprehension latent trait at the end of 4^{th} grade. Byrne et al. (in press) conducted a genetic factor analysis across a wide range of preschool and second-grade measures that included five on-line learning tasks and measures of vocabulary, letter identification, and sight and nonword reading. Three correlated genetic factors emerged, the first factor for vocabulary, the second factor for second-grade word and nonword reading, second-grade orthographic learning, and preschool letter knowledge, and the third factor for tests of verbal short-term memory. The second print-related factor showed the most genetic specificity. The results support the importance and distinctive genetic etiology of learning print-speech integration that was partly independent from genetic factors affecting spoken language and verbal short-term memory.

Taken together, results from the CLDRC and the ILTS studies have shown low to moderate genetic correlations between word decoding and oral language. They highlight the importance of partly independent genetic influences on paired associate learning between print and speech for the development of word recognition. But the partly independent genetic influences on oral language so critical for reading comprehension also deserve attention in both research and education. They suggest that interventions need to focus on both print-speech associations and higher language skills, perhaps differentially depending on children's skill profiles and partly independent learning constraints in the development of decoding and oral comprehension.

Genetic and Environmental Etiology of Longitudinal Stability in CLDRC Twins

The CLDRC twins have been recruited across a broad age range between 8 and 18 years. Most previous examinations of developmental differences in this sample have been cross-

sectional (cf., Keenan et al. 2008). However, a sub-sample of CLDRC twins initially tested at a mean age of about 10 years have been retested at a mean age of about 16 years (Betjemann et al., 2008; Hulslander, Olson, Willcutt, & Wadsworth, 2010). Betjemann et al. reported high stability of reading performance and high genetic correlations over this interval for individual word-reading and comprehension measures. Hulslander et al. subsequently found nearly perfect phenotypic stability for individual differences when reading and related skills were modeled as latent traits to remove contamination from measurement error. The latent-trait longitudinal correlations were r = .98 for word recognition, r = 1.0 for phonological awareness, r = .93 for phonological decoding, and r = .95 for spelling. It seems that the vast majority of children establish a very stable developmental trajectory for growth in reading and related skills by age 10 years. To better understand the origin of these individual differences in developmental trajectories, we now turn to the development of reading and related skills from preschool at mean age 4 years 10 months through the end of fourth grade at mean age 10 years.

The International Longitudinal Twin Study (ILTS)

Much of the twin research that we have reported at SSSR conferences over the past decade has come from unselected population samples of twins tested on the same measures in Australia, Colorado, and Scandinavia (Norway and Sweden combined). The twins were initially tested on pre-reading skills in their homes or preschools during the year prior to kindergarten entry (Byrne et al., 2002; Samuelsson et al., 2005). They were subsequently tested on reading and related skills at the end of kindergarten, first grade, and second grade in all three countries, and also at the end of fourth grade in Colorado (Olson et al., 2011).

At preschool in all three ILTS samples, most individual differences on a print-knowledge latent trait, primarily based on letter name and sound knowledge, were due to differences in shared family environment (A = 20% - 26%; C = 62% - 74%) (Samuelsson et al., 2007). The vast majority of preschool children could not read, so we could not estimate genetic and environmental influences on their reading ability. By the end of kindergarten, most children could read enough words and nonwords on the TOWRE so we could estimate genetic and environmental influences on their individual differences (Samuelsson et al., 2008). Those individual differences were mostly due to genes in Australia (A = 84%; C = 9%) and Colorado (A = 68%; C = 25%). In contrast, individual differences for the Scandinavian twins' reading at the end of kindergarten were mostly due to shared environment (A = 33%; C = 52%). Samuelsson et al. noted that reading is not formally taught in Scandinavia until the first grade, so the Scandinavian twins' reading scores were significantly lower than for the Australian and Colorado twins. Thus, it was variation in the twins' shared home, preschool, and kindergarten environment that was the major influence on individual differences at the end of kindergarten in Scandinavia. However, after all children had received a year of formal reading instruction at the end of first grade, genetic influence was about as strong in Scandinavia (A = 79%; C = 7%) as it was at the end of first grade in Australia (A = 80%; C = 2%) and Colorado (A = 83%; C = 7%). Similarly high genetic and low shared environment estimates have been found for spelling and reading comprehension at the end of first grade, and the genetic correlations between word recognition, spelling, and reading comprehension were all above r_g = .9 (Byrne et al., 2007). The pattern of high

genetic and low shared-environment estimates continued to the end of second grade in all three samples (Byrne et al., 2009), and to the end of fourth grade in Colorado for word and nonword reading, reading comprehension, and spelling (Christopher et al., 2013; Olson et al., 2011).

The bottom line is that after a year of formal reading instruction, individual differences in word reading, spelling, and reading comprehension are highly influenced by genes in the independent twin samples from the Sydney area of Australia, from the Denver area of Colorado, and from southern Norway and Sweden. Of course environmental influences do have a big effect – they affect the level of reading in the population because we learn to read in classrooms and homes. However, on average, the variation across the twins' shared home and classroom environment has relatively little influence on individual differences in reading once children have completed a year of formal reading instruction. When compared to the strong shared environment influences on preschool print knowledge, it seems that what formal reading instruction in schools does is to considerably reduce the environmental variance for reading development in all of the ILTS sampling areas. This is a very good result. It would be unfortunate if strong family-based environmental influences persisted beyond the early stages of school. Indeed, this is partly what schools are about, overcoming factors that produce big differences among kids before they go to school, particularly when those environmental influences are negative.

Results from Other Longitudinal Twin Studies

It is important to ask if other twin studies find similar results to the ILTS. The Twins Early Development Study (TEDS) is being conducted with a very large population sample in England and Wales. Harlaar, Spinath, Dale, and Plomin (2005) administered the TOWRE word and nonword tests over the phone to 3909 twin pairs at mean age 7.07 years near the end of first grade. Based on a composite measure including both TOWRE word and nonword reading, they reported estimates of genetic (A = 66%) and shared environment (C = 18%) averaged across gender, not much different from the ILTS estimates at the end of first grade near the same mean age, and well within our 95% confidence intervals. However, it is possible that the slightly lower genetic and higher shared-environment estimates in the TEDS sample compared to the three ILTS samples reflects a greater environmental range across its national sample in the U.K. It is also possible that their administration of the TOWRE by telephone was more influenced by the home environment than the TOWRE administered directly by testers in the ILTS samples.

A recent large twin study in Florida analyzed scores for 2570 twin pairs on the school-administered one-minute Oral Reading Fluency (ORF) test (Taylor & Schatschneider, 2010). They reported genetic (A = 62%) and shared environment (C = 22%) estimates from near the end of first grade at mean age 6.6 years. Their sample was more socioeconomically diverse than the ILTS samples, and they offered that as a potential explanation for their lower genetic and higher shared environment estimates compared to the ILTS results. Also, when they separated their sample into the lower 25%, the middle 26%-74%, and the highest 25% for median family income based on geographic area, they found that the lowest income group had the lowest genetic (A = 45%) and highest shared environment influences (C =

37%) of the three income groups. This result may be similar to what Friend et al. (2008) found for the relations between parents' years of education and levels of genetic and environmental influences on reading disability.

A third twin study is being conducted in Ohio by Stephen Petrill and colleagues. They initially measured several reading and related skills in their twin sample at mean age 6 years (similar to the Colorado ILTS mean age at the end of kindergarten), and they retested the twins each year after that out to mean age 12 years (Logan et al., in press). In one of their earlier papers, Petrill et al. (2007) examined the etiology and longitudinal stability of early reading, assessed at their first two waves of data. Looking at their first wave (when twins were in kindergarten or first grade), estimates for letter knowledge showed significant genetic and shared environmental influences (A = 35%, C = 38%), word recognition showed genetic and shared environmental influences (A = 55%, C = 34%), pseudoword decoding demonstrated significant genetic and shared environmental influences (A = 56%, C = 26%) and reading comprehension showed genetic and shared environmental effects (A = 50%, C = 21%). Results in the second wave were highly similar, with the exception of passage comprehension, which showed high genetic and nonsignificant shared environmental influences (A = 76%, C = 11%). Subsequent papers reporting estimates from later assessment waves suggest that genetic influences on reading outcomes remain statistically significant whereas shared environmental influences become small or nonsignificant (see Harlaar et al., 2010).

In summary, the TEDS and Florida twin studies report results that are basically consistent with those from the three independent ILTS twin samples: genetic influences are substantially greater than shared environment influences when word reading is tested at or near the end of the first year of formal reading instruction, and this pattern continues across the early grades. The attenuated genetic and stronger shared environmental influences found in the early assessment waves in the Ohio twin study may have been due to its very broad within-wave range in months of education (beginning of kindergarten through the end of first grade) at their first assessment wave.

Biometric Growth Models of Early Reading Development

Biometric growth models of early reading development were first introduced by Petrill et al. (2010). These models are able to distinguish the average genetic and environmental etiologies for where children start in reading development, defined as the intercept, and for their subsequent growth patterns across the grades. To date, these models have been applied to longitudinal twin data from Australia, Colorado, and Scandinavia (Christopher et al., 2013; in press), Florida (Hart et al., 2013), the U.K. (Harlaar, Dale, Hayiou-Thomas, & Plomin, 2012), and Ohio (Logan et al., in press; Petrill et al., 2010). The studies vary in exactly how the initial intercept is defined (end of kindergarten, beginning of first grade, or end of first grade), measures employed (word recognition, oral reading fluency, reading comprehension, spelling), and modeling assumptions (linear vs. non-linear, correlation of errors).

The details of these recent biometric growth model studies are beyond the scope of this paper. In summary, most of the biometric growth model studies to date showed high A and

low C at the first wave intercept as well as high A and low C for univariate estimates across each of the waves. Results from the Ohio twin sample showing high C and low A were an exception to this pattern. We surmise that this was due to the very wide range of months of education that are shared by twins in a pair (beginning kindergarten through end of first grade) at their first wave intercept. The other studies with the opposite high A and low C results at intercept had a much more narrow range for months of schooling. The one exception was for Scandinavia, with approximately equal influences from A and C at the end of kindergarten (Christopher et al., in press), a result that we previously noted was due to the lack of reading instruction in Scandinavian kindergartens (Samuelsson et al., 2008).

The results for linear and quadratic growth were more mixed. The A and C influences on growth seem to depend partly on measures, samples, fitting linear versus nonlinear models, and models allowing or not allowing unique variances (twin similarities not related to growth) to correlate (see Christopher et al., 2013, for a comparison of models with correlated or uncorrelated errors). We concur with Christopher et al. that allowing unique variances to correlate is the most appropriate model, though this is still a debated question. Either way, variance in growth is generally much lower than variance in the intercept, and growth variance has relatively little relation to univariate estimates of genetic and environmental influence across the grades for twin samples from Australia, Colorado, Florida, Scandinavia, and the UK.

Summary

In summary, the evidence suggests that the answer to the title question, “Why do children differ in their development of reading and related skills?” is on average, after the first year of formal literacy instruction, mostly the genetic differences between children. The mostly genetic conclusion is consistently supported from samples of identical and fraternal twins tested in Australia, Colorado, Florida, Scandinavia, and the UK near the end of first grade, and in Ohio by mean age 9 years. It is also supported for older twins tested in the CLDRC and in the U.K. TEDS study. The genetic and shared environment influences on growth are less consistent across studies and measures, but regardless of whether shared environment influences on growth are relatively high or low, variance in growth is low, and it has little influence on univariate A and C estimates at any given age or grade. We also found that the relevant genes depend at least partly on the specific reading and related skills being assessed (e.g., word decoding, listening comprehension, reading comprehension). But there are important qualifications to the “mostly genetic” conclusion. It is to these that we now turn.

Qualifications and Clarifications

Assumptions of Additive Genetic Influence and no Assortative Mating

Here we add a sixth qualification to the five mentioned in the introduction. The models used in all of the reviewed twin studies assume additive genetic influence (no dominance or epistasis) and no assortative mating indicated by correlations between parents. Violations of these two assumptions tend to bias genetic and environmental estimates in opposite directions: genetic effects would tend to be underestimated if there is assortative mating, and overestimated if there is dominance or epistasis (Carey, 2003; Keller & Coventry, 2005;

Keller, Medland, & Duncan, 2010). In any case, converging evidence from the Colorado Adoption Project comparing genetically unrelated siblings shows very low shared-environment influences on reading (Wadsworth, Corley, Hewitt, Plomin, & DeFries, 2006), consistent with the low shared-environment estimates from the reviewed twin studies. Any potential bias in the estimates from the twin studies would not be sufficient to challenge the basic finding that individual differences and deficits are primarily due to genetic factors in the sampled populations.

Dependence of Genetic and Environmental Estimates on the Environmental Range

In the introduction we emphasized that the average balance of genetic and environmental influences across a twin sample depends on the relevant environmental range in that sample. Unfortunately, it is difficult to quantify the relevant environmental range for reading in different published twin studies beyond a comparison of their estimates of environmental influences from the behavior-genetic analyses. But in principle, twin samples with greater reading-relevant environmental variance are likely to show lower average estimates for genetic influences and higher average estimates for environmental influences on individual differences or deficits in reading. Also, it is important to keep in mind that even when behavior-genetic estimates of the average environmental influence within a sample are low, there can be extreme cases of poor reading within the sample that are entirely due to environmental influences, such as a particularly poor home, peer, or classroom environment for reading.

Importance of the Environment is not Inconsistent with High Genetic Influence

Our acknowledgement of the importance of environmental range and the possibility of strong environmental influences on individual cases within twin samples does not diminish our conclusion that genes are the main average influence on individual differences in children's reading ability. Yet the reading environment is obviously important for reading development. For example, if the emphasis on reading instruction in the early grades were to double in time and intensity (cf., Sadosky & Wilson, 2006), the resulting increase in average reading ability would be entirely due to this environmental change. However, the etiology of individual differences after this environmental change, i.e. what accounts for the differences between individuals all exposed to increased reading instruction, would continue to be mostly genetic influences.

The Evidence for Classroom Effects

Those who believe that the environment is the main influence on individual differences in reading sometimes assert that they are due to differences in teacher quality. This view is constantly reinforced by the U.S. media and politicians. They blame teachers for children's reading difficulties, although interestingly, they do not readily give teachers credit for the high achievers in their classes, nor is there recognition of environmental and genetic influences on students that are outside teachers’ control. So let's look at the evidence for this predominant environmental assumption. If there is direct evidence for very strong environmental influences from classrooms (including teachers) on individual-differences variance in early reading, that would contradict the low environmental estimates from behavior-genetic twin studies.

There is one large experimental study with random assignment of teachers to classrooms and students to teachers in Tennessee (Nye, Konstantopoulos, & Hedges, 2004), and three quasi-experimental studies with twins (Byrne et al., 2010; Hart, Taylor, & Schatschneider, in press; Kovas, Haworth, Dale, & Plomin, 2007). The Nye et al. study found that classroom effects (these include teachers as well as other aspects of the classroom such as paraprofessional resources and peer influences) on average classroom performance accounted for only 7% of the individual-differences variance in children's reading ability in grades 1 – 3.

The other evidence comes from twin studies that assess whether members of twin pairs are in the same or different classrooms; classroom effects can be estimated from the difference in twin similarity as a function of sharing or not sharing a classroom. The twin study by Byrne et al. (2010) estimated classroom effects on Australian and Colorado ILTS twins' reading and spelling performance in kindergarten, grade 1, and grade 2. Based on the difference in correlations for the same- vs. different-classroom twin pairs, classroom effects were estimated at 8% across the same Australian and Colorado ILTS samples that were used in the behavior-genetic analyses reported in the individual differences section of the present paper. When the twins' performance was controlled by their performance in the previous year, the "value added" classroom effects averaged only 4%.

Kovas et al. estimated classroom effects by comparing their shared environment estimates on TOWRE word and noword reading at the end of first grade between twins in the same class room (C = .17) versus twins in different classrooms (C = .07). While this difference was not statistically significant in their large sample, it suggests a small shared- versus non-shared classroom environment effect on individual differences of around 10%, similar to the other estimates we have reported.

Finally, Hart et al. (in press) tested the difference in oral reading fluency (ORF) at the end of second and third grade for twins that were in first-grade classrooms with growth below the mean versus classrooms with growth above the mean in ORF across the year. The effect sizes for twin pairs discordant for first grade classroom ORF growth were statistically significant but small, and they conclude that "...the effect of teacher quality on student reading outcomes is small."

In sum, the average classroom effect on individual differences in early grade reading has consistently been found to be small. Of course, extremely effective or ineffective teachers can have very positive or negative influences that are not obvious from the very modest average influence of classroom differences on early reading development. We do not mean to deny the importance of strong teacher training and monitoring of continued professional development. However, we wish to emphasize that it is important not to characterize classroom performance differences as an index of "teacher quality," as was done in the Hart et al. (in press) study and the earlier studies by Nye et al. (2004), Taylor and Schatschneider (2010), and Taylor et al. (2010). Using mean classroom performance or classroom growth across the school year for the evaluation of teacher quality is complicated by many other influences on average classroom performance, such as the factors collectively referred to as "classroom climate," exemplified by the students' perceptions of their class's attitude to

learning, and which are independent of particular teachers (Marsh, Martin, & Cheng, 2008), and by variation across classrooms in children's self-regulation skills (Skibbe, Phillips, Day, Brophy-Herb, & Connor, 2012). Average classroom performance will also be influenced by the genetic and classroom-independent environmental influences on individual students' reading skills. Therefore, the use of classroom performance differences to rate "teacher quality" can be quite misleading, and often unfair, in this era of blaming teachers for children's learning difficulties in reading and related skills (cf., Alter, 2007).

Implications of Genetic Influences for Educational Policy

The evidence for strong genetic influences on individual differences and deficits in reading may seem discouraging to many educators, but results from behavior-genetic studies also suggest *how* genes influence reading development in ways that offer avenues for intervention. The question of how genes influence reading has two educationally relevant answers that we will consider here. One is that genes influence learning rates for reading and related skills. The other is that genes influence the environment through a gene - environment correlation.

The Byrne et al. (in press) genetic factor analysis we reviewed earlier and Byrne et al., (2008) included on-line learning measures that demonstrated substantial genetic influences on learning rates for reading and related skills. The implication for education is that depending on the severity of reading difficulties, much more reading practice, possibly including computer or tutor support for decoding difficulties, may be required for a child with genetically constrained learning rates for reading accuracy, fluency, and comprehension to reach or more closely approach the "grade-level" criterion (average performance) that was originally required of "all children" by 2014 (107th Congress, 2002).

Unfortunately, the second thing we have learned is that genetic constraints on learning rates for reading development are likely to result in less than normal reading practice, and thus a gene-environment correlation that works against the need for greater reading practice. Olson and Byrne (2005) noted that there is significant genetic influence on a title-recognition measure of print exposure. Harlaar, Dale, and Plomin (2007) found that genetic influence on word recognition at age 7 in the U.K. was highly correlated with genetic influence on an author recognition test at age 10, and with prior reading ability. Moreover, after controlling for genetic and environmental influences shared by age-7 word recognition and age-10 author recognition, there was evidence for a separate shared environmental link between age-10 author recognition and age-12 word recognition. In the Ohio twin sample, Harlaar, Deater-Deckard, Thompson, DeThorne, and Petrill (2011) recently confirmed a gene-environment correlation between independent reading rated by the twins and their care givers at age 11 and their reading achievement at age 10.

The educational implications of compromised learning rates and the gene-environment correlation are daunting for children with reading disabilities, their parents, their teachers, and their schools. The extra instruction and reading practice needed to at least partly compensate for children's reading problems may be difficult to accommodate and motivate in a typical school day filled with other academic demands. Of course, greater reading practice and instruction could be supported for all children if the school day and school year

were longer. But with the short school days and years common in most western societies, compensatory reading practice often has to be supported in after-school classes and in the home. This raises a range of motivational issues because many children with reading disabilities would often rather be doing anything but reading after school and in their home. That is why organizations such as the International Dyslexia Association emphasize the importance of developing adequate reading skills, the payoff for working extra hard to improve those skills, and the transfer of that work ethic to other areas of life. Teachers can certainly help to provide this motivation, but they often need the support of the family and broader school environment do so.

Conclusion

The foregoing discussion of how genes influence individual differences and deficits in reading raises the question of what are the reasonable expectations for children with reading disabilities, and for their parents, their teachers, and their schools. So here, in conclusion, we will grab the third rail of educational discourse and say that our expectations for a child's reading achievement may often be too high. We are aware that diminished expectations can result in children failing to reach their “potential” level of reading achievement, and we should guard against that. But the definition of “potential” at the individual level is complicated by genes and sometimes hidden environmental constraints, or at least ones that are beyond control, as well as the values of the society, the family and the child. Certainly the most optimistic and well-meaning, but absurd, criterion is for *all* children to be at least at “grade level” (typically defined as average performance for grade on standardized tests) as specified by the No Child Left Behind law (107th US Congress, 2001). Similar demands for high literacy in all children are included in the Common Core Standards (2010) adopted by most States in the U.S., which seek to “....ensure that all students are college and career ready in literacy no later than the end of high school.” While some of the requirements of the No Child Left Behind law have been relaxed, the sentiment is still expressed in many State education laws that all children must meet some minimal criterion, that teachers should be evaluated on their students’ reaching that criterion, and that children failing to meet criterion by the end of third grade should be retained in grade until they do (Rose, 2012).

The relations of values to criteria for reading achievement are not often considered, but we think they should be, and the values should include those of the child and the family. Just how much additional reading practice and remedial instruction should be expected or required for children who are slow in their reading development? Some children with slow learning rates for reading and related skills may choose to devote much more than normal practice in reading at the expense of other activities to reach or more closely approach “grade level.” Other children may place less value on their reading proficiency, and more on other academic and non-academic activities.

We believe that all children should have strong support for their reading development, including the opportunity for additional intensive instruction for those with learning difficulties in reading. But the evidence for strong genetic influences on many reading difficulties, including reading fluency that seems most resistant to intervention (Torgesen et al., 2001), requires a much more nuanced approach to reading-ability expectations for

children than those reflected in U.S. Federal and State laws. Currently these laws and public expectations for all children's reading achievement can be quite unfair to many children with reading difficulties, their parents, their teachers, and their schools.

In this review we have emphasized the role of genes in influencing the course of reading development. Our motivation has been in part to counter the view, common enough in the social sciences, that the environment is where most of the action is (Pinker, 2002). But in conclusion we want to remind readers that environmental influence is important too, as shown by the estimates of around 30% shared environment for reading disability and around 20% shared environment in the TEDS and Florida population studies of individual differences near the end of first grade. In addition, there is evidence that some of the high genetic influence on reading ability is due to a gene-environment correlation for reading practice, further emphasizing the importance of the reading environment in reading development. Even if estimates of shared environmental variance are very low in a twin sample, that may only suggest a very narrow effective environmental range in that sample. It does not preclude changes in the environment to improve reading at the low end of the distribution in that sample, as well as across the whole sample. Thus, regardless of the levels of genetic and environmental influence in a population, there is always room for well-designed interventions, including extended reading practice, and research should continue into the most effective interventions for reading difficulty and for improving literacy in the population as a whole.

Acknowledgments

Funding was provided by the National Institutes of Health, grant numbers P50 HD027802 for the Colorado Learning Disabilities Research Center, and R01 HD038526 for the Colorado component of the International Longitudinal Twin Study (ILTS). The Australian component of the ILTS was supported by the Australian Research Council, A79906201, DP0663498, DP0770805. The Scandinavian component of the ILTS was supported by the Research Council of Norway 154715/330, the Swedish Research Council grants 345-2002-3701, PDOKJ028/2006:1, and 2011-1905, and the Swedish Council for Working Life and Social Research (2011-0177). We thank the twins and their families who participated in our research. The Australian Twin Registry is supported by an enabling grant from the National Health and Medical Research Council.

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