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## Genetic and Environmental Influences on Aspects of Literacy and Language in Early Childhood: Continuity and Change from Preschool to Grade 2

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### Abstract

Early literacy and language skills of twin children in the USA, Australia, and Scandinavia were explored in a genetically sensitive design (maximum  $N = 615$  pairs). For this article, we report aspects of preschool and Grade 2 data. In Grade 2, there were strong genetic influences on word reading, reading comprehension, and spelling. Vocabulary was about equally affected by genes and shared environment. Multivariate analyses indicated substantial genetic overlap among the Grade 2 literacy variables. Longitudinal analyses showed that genetic factors evident at the preschool stage continued to affect literacy and vocabulary three years later in Grade 2, but there was also evidence of new genetic factors coming into play over the time interval, at least for literacy. Suggestions are made about the search for underlying biological and cognitive processes, and educational implications are explored.

### Keywords

Behaviour genetics; literacy development; vocabulary; word reading, reading comprehension; spelling

### 1. Introduction

In this article we explore the extent to which genes and aspects of the environment influence variability in literacy development. We do so by continuing to report results from a genetically-sensitive longitudinal study of twin children as they develop in reading and spelling. Specifically, the empirical issues that we address are (1) the relative influence of genes and environment on Grade 2 reading, spelling and vocabulary, and (2) how genetic and environmental influences contribute to continuity and change in the early school years. The first issue is familiar as the “nature-nurture” question. The second may be less familiar. The

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goal is to identify the degree to which developmental stability and change at the behavioural level can be attributed to stability and change in genetic and environmental influences. In literacy, the results of research on this question can have practical implications, as well as being of scientific interest. For example, if an additional genetic source starts to affect reading in, say, Grade 2, teachers may see children changing developmental trajectories at that stage without obvious changes in teaching practices, something that might otherwise appear mysterious. Or if a new environmental factor comes into play as children develop, knowing about it could be put to good effect with all children.

### 1.1. Empirical background

In the International Longitudinal Twin Study (ILTS) of the genetic and environmental influences on children's early progress in literacy we are assessing monozygotic and same-sex dizygotic twin children recruited in the last year prior to formal schooling and followed through the first years of school. The sample is from Australia, Norway, Sweden, and the USA. We have already reported on the preschool phase (Byrne et al., 2002; Samuelsson et al., 2005; Willcutt et al., 2007), and on progress from preschool to (a) kindergarten (Byrne, et al., 2005, 2006; Samuelsson, Olson et al., 2007) and (b) Grade 1 (Byrne, et al., 2007, Samuelsson, Byrne, et al., 2008). We have also described analyses centred on the acquisition of novel spelling patterns from our Grade 2 assessment and the interaction of that process with established spelling ability and nonword decoding (Byrne et al., 2008), and we will summarize those latter results below. The primary purposes of this article are to extend the Grade 2 coverage to include measures of word reading, reading comprehension and vocabulary, and to trace the phenotypic, genetic and environmental relations between selected preschool abilities and second grade performance.

Reading problems aggregate in families (Thomas, 1905), and there is now abundant evidence that this is in part due to the fact that families share genes and not just environments. The heritability of dyslexia is put at between .5 and .6, and variability in reading ability across the normal range is at least as heritable, with estimates ranging from .5 to .8 for various aspects of reading and spelling (for reviews, see Olson & Byrne, 2005; Pennington & Olson, 2005).

Aspects of the environment also play a role in determining variability in literacy levels, including situations that twins share such as the home literacy environment and early school practices (Byrne et al., 2005; Harlaar, Spinath, Dale, & Plomin, 2005; Petrill, Deater-Deckard, Thompson, DeThorne, & Schatschneider, 2006). However, in our project, estimates of this type of environmental influence have generally been modest, and have tended not to last as school progresses (Samuelsson, Byrne, et al., 2008). We can again check on this with the current analyses of the twins' third school year results.

Monozygotic (MZ) twins share all of their genes whereas dizygotic (DZ) twins share, on average, half of their segregating genes. This amounts to a kind of natural experiment that allows researchers to separately identify genetic and environmental factors governing individual differences in a trait. It relies, among other things, on an assumption that within families both types of twins share equally similar environments, an assumption that allows researchers to distinguish family-based ("shared") environment influences from those that independently affect members of twin pairs ("nonshared environment"). For trait variability that is fully determined by genetic variability, the within-pair monozygotic twin correlation will be 1.0, assuming no measurement error, and dizygotic twins will correlate .5. For characteristics that are fully determined by shared environment, the correlation for both types of twins will be unity. For characteristics that are fully determined by nonshared environment, twins will be no more alike than randomly selected individuals (correlation = 0 for both twin types). These are idealized situations, but departures from these ideals can be used to estimate the mix of genetic and environmental (shared and nonshared) factors affecting the characteristic

of interest. See Plomin, De Fries, McClearn, & McGuffin (2008) for an introduction to twin methodology.

In the on-going ILTS, we elected to begin with preschool children, before formal literacy instruction has begun, to avoid the confounding effects of reading levels themselves in interpreting genetic and environmental influences on known correlates of literacy development. In particular, we assessed phonological awareness, letter knowledge and other aspects of print awareness, verbal fluency (rapid automatized naming), verbal short-term memory, learning ability across a variety of task types, vocabulary and other “higher” language functions such as morphology, and nonverbal measures such as Block Design. We also collected information from parents relating to home literacy and to the children’s levels of attention and hyperactivity.

During the school years our test battery includes word and nonword identification, reading comprehension, aspects of spelling, phonological awareness, verbal short-term memory, vocabulary and grammatical processes. We also continue to collect questionnaire data from parents.

At the preschool level, using a sample of 312 pairs of MZ twins and 312 same-sex DZ pairs, we have shown that some abilities are subject to substantial genetic influence; the literacy-relevant variables of phonological awareness, rapid naming, and verbal memory. The equally literacy-relevant variable of print knowledge, in contrast, is more subject to influence from factors in twins’ shared environments, likely to be located in the home and/or preschool. Shared environment was also the major influence on our measures of vocabulary, morphology, and syntax. For full details, see Byrne et al. (2002) and Samuelsson et al. (2005).

At the end of the first school year (kindergarten), reading, spelling, phonological awareness, and rapid naming are already seen to be substantially heritable, with estimates of .70, .39, .63, and .60, respectively. Grammatical control continues to mainly show shared environment effects (.40, versus .21 for heritability). For full details, see Byrne et al., (2006; sample sizes, 213 MZ pairs, 209 DZ pairs). Grade 1 data show a continuation of high heritability levels for reading and spelling, with estimates of .82 for word identification, .76 for reading comprehension, and .71 for spelling (Byrne et al., 2007; sample sizes, 167 MZ pairs, 152 DZ pairs).

(Note that sample sizes in different reports vary for two reasons; the project is longitudinal and continuing, with new cohorts added each year, meaning that more twins will have been assessed at earlier phases than later ones; in some analyses, we have excluded the Scandinavian sample at kindergarten because of substantial differences in school culture such that reading and writing are not generally taught in that first school year—see Samuelsson, Byrne et al. [2008] for a discussion and comparative analysis of country differences. Attrition from year to year is virtually zero—only a handful of families have left the project, and almost always because they have moved out of the respective geographical regions.)

As well as generating univariate estimates, it is possible to conduct multivariate analyses to estimate the degree of genetic overlap and independence among variables, as well as environmental (shared and unique) overlap and independence among them. This can be done for variables measured simultaneously, for example in the preschool phase, and variables measured successively, for example at preschool followed by kindergarten.

In exploring continuity and change, we have employed the Cholesky decomposition model (Neale, Boker, Xie, & Maes, 2002), similar in principle to hierarchical regression, where the effects of an independent variable on a dependent variable are assessed after the effects of another, correlated predictor are taken into account. So, this method permits an assessment of

genetic, shared environment and nonshared environment influences that are common to two or more measured variables and those same influences that are specific to each measured variable. See Figure 1. Multivariate approaches can also be couched in terms of genetic, shared environment and nonshared environment correlations among measures, or the degree to which individual differences on different measures share the same genetic and environmental influences.

Longitudinal Cholesky analyses showed that phonological awareness and rapid naming are each subject to both genetic continuity and genetic change in the progression from preschool to kindergarten. That is, for each of these variables one genetic source exerts influence at both phases and a second comes into play in kindergarten as well (Byrne et al., 2006). We also tracked genetic and environmental influences on preschool print knowledge, phonological awareness, and rapid naming in relation to kindergarten reading. Reading was influenced to a substantial degree by genes that were common to all three preschool variables, an example of what Plomin and Kovas (2005) have referred to as “generalist genes.” This genetic source accounted for the majority, 76%, of the total heritability of kindergarten reading, which we estimated at .69. Perhaps the most noteworthy aspect of this analysis is that preschool phonological awareness and rapid naming, both with heritabilities of .6 or over, shared genetic variance with reading only through the genes that also determine preschool print knowledge, the generalist genes. This may underlie the often-observed fact that early letter name knowledge, which constituted a substantial part of our print knowledge composite, is the best predictor of subsequent reading levels, even though letter knowledge typically reaches ceiling by the end of the first school year (Foulin, 2005). Apparently, preschool letter knowledge depends in part on genes that subsequently play a substantial role in school reading levels.

Shared environment also contributed to continuity from preschool to the first school year. All preschool measures were influenced by shared environment, substantially in the case of print knowledge and modestly in the cases of phonemic awareness and rapid naming. Reading was also affected by this source, although also to a modest extent (10% of total variance).

Across the two school years, kindergarten to Grade 1, continuity and change were both in evidence again for reading, with new genetic influence coming into play in Grade 1 in addition to genes that also affected kindergarten reading (Byrne et al., 2007). The new genetic source accounted for approximately 22% of the total heritability of reading. For spelling, a single genetic source across the two years was the only statistically significant influence. Shared environment was a negligible source of variance in Grade 1 for either reading or spelling. Unique environment, though accounting for modest amounts of variance (range, 8% to 0.5%), also followed the pattern of continuity plus change—an environmental effect common to both school years and one specific to Grade 1.

As indicated earlier, we have already conducted one set of analyses on the Grade 2 data in our project. It involved spelling, orthographic learning, and decoding (Byrne et al., 2008). Spelling was assessed using the Spelling subtest of the Wide Range Assessment Test-Revised (WRAT-R; Jastak & Wilkinson, 1984). Orthographic learning was tested with a technique originally devised by Share (1999) in which children read short passages harbouring novel words that can be spelled in more than one way, such as *laif*, and are subsequently asked to spell those words. Decoding was derived from the accuracy with which the children read the novel words. The three variables, spelling, orthographic learning, and decoding, were each substantially heritable, with estimates of percent variance due to genes of 74, 43, and 68, respectively. Most notably, the genetic correlations among the variables approached unity (values of .85 to .97), evidence that the same genes are implicated in these abilities. We favoured an interpretation that identified a learning-rate parameter as the underlying, uniting process. Thus, we saw both current spelling ability levels and established decoding ability as the “crystallized” products

of this process, one that is tapped directly by the orthographic learning task. Other aspects of our analyses favoured this common-gene interpretation over alternatives, one of which was that decoding exerts a direct causal influence on the acquisition of new spelling patterns, as expressed in Share's (1999, 2004) self-teaching hypothesis. The data underline the importance of genes that affect the rate at which print-speech connections are established as determinants of literacy development.

In this article we turn our attention, first, to a wider-ranging analysis of Grade 2 results. The new tests that we analyse include word reading, reading comprehension, and vocabulary, and we update the spelling data in view of a slightly larger sample size in this ongoing project. Then we trace the phenotypic, genetic and environmental relations between those preschool measures and the second grade literacy variables in the search for evidence on sources of continuity and change across this three-year period.

## 2. Method

### 2.1. Participants

The sample at Grade 2 consisted of 303 monozygotic twin pairs, (185 US, 86 Australian, and 32 Scandinavian [Norway and Sweden combined]) and 312 dizygotic pairs (220, 49, and 43), total 615 pairs. The twins were recruited from birth records in Colorado and Scandinavia, and from the (volunteer) Australian Twin Registry in Australia. Zygosity was determined from DNA collected via cheek swabs, or in a minority of cases from selected items from the Nichols and Bilbro (1966) questionnaire. Mean ages (*SD*) in months were 100.8 (3.8), 94.2 (3.5), and 104.1 (3.7) for the US, Australian, and Scandinavian samples, respectively. These age differences are all significant ( $p < .001$ ). Scandinavian children start school at a later age than those in the other countries, and the US children were tested in the summer after the school year while Australian children were tested during the final three or four months of the school year (owing to the shorter summer vacation in Australia of six weeks versus twelve in the US). As will be seen in Results, the Australian children generally outperformed the US children, so the higher ages and months of schooling in the US sample has not resulted in superior performance. The Scandinavian children were superior in spelling, perhaps due to their more regular orthography, but their word recognition and comprehension scores were lower, perhaps due to the later start on reading instruction in Scandinavian schools.

### 2.2. Materials: Grade 2

**Test of Word Reading Efficiency (TOWRE)**—In this test (Torgesen, Wagner, & Rashotte, 1999), children read a list of words and a list of nonwords as quickly as possible, with the score being the number correctly read in the 45 seconds allowed. The two subtests are referred to as *Sight Word Efficiency (SWE)*, and *Phonemic Decoding Efficiency (PDE)*. There are two equivalent forms of the test, Forms A and B. We administered both to optimise the reliability of the scores. The SWE and PDE scores in Table 1 are the averages from the two forms.

*Woodcock Passage Comprehension* from the Woodcock Reading Mastery Test-Revised (Woodcock, 1989). This test uses a cloze procedure to assess the child's ability to understand passages of connected text.

**Spelling**—We used the Wide Range Achievement Test (WRAT) spelling subtest. Children spell words until they make ten consecutive errors, with items ranging from simple words like *bed* to complex ones like *belligerent*. Score is total number correct, maximum = 45.

**Vocabulary**—We selected the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 2001), a confrontation naming measure in which the child is required to name pictures of 60 concrete objects, ranging from common ones like bed to rarer ones like abacus. We administered all 60 items. The test has options for recognition naming and phonological hints for items when recall fails, but we did not exercise those options. Thus the vocabulary score was simply the number of items correctly named.

### 2.3. Materials: Preschool

The measures taken in the preschool phase of the project and used in the longitudinal analyses that we report here included the following: Print Knowledge, comprised of letter recognition from names and sounds; Concepts about Print (Clay, 1975), and familiarity with common signs such as *stop*; Phonological Awareness, comprised of elision (word, syllable, and phoneme), blending (syllable and phoneme), and matching of rhymes and initial and final phonemes; Rapid Naming, comprised of objects and colours from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999); Vocabulary, a confrontation naming test known as the Hundred Pictures Naming Test (Fisher & Glennister, 1992). Testing took place over five sessions within a one- or two-week period, either in the twins' homes or their preschools. Full details are presented in Samuelsson et al. (2005).

### 2.4. Procedure

The Grade 2 children were tested in their schools or homes in a session lasting about one hour. Two testers assessed each twin pair at the same time, one tester per child, except in the Scandinavian sample, where just one tester per pair was available. The procedure for the preschool assessment is described in Samuelsson et al. (2005).

## 3. Results

### 3.1. Phenotypic data: Grade 2

Mean scores by country are presented in Table 1. The TOWRE and Woodcock Passage Comprehension values are standard scores based on the tests' norming samples to illustrate the representativeness of the samples. Boston Naming Test scores are raw values. All country differences within the reading and spelling measures were significant with the exceptions of the contrast between the US and Scandinavia on nonword reading and between the US and Australia on spelling. We do not have a ready explanation for the low levels of the Scandinavian sample on sight words and comprehension, although the fact that the tests were translated for this project may make the comparability with their use in the English-speaking samples uncertain. Also, there is no formal reading instruction in Scandinavian kindergartens, in contrast to systematic reading instruction in Australian kindergartens, and variable kindergarten instruction in the U.S. sample (Samuelsson, Byrne et al., 2008). The greater regularity of Norwegian and Swedish orthography may account for both the adequate nonword performance and superior spelling result. The Australian children had higher scores than their US counterparts except on spelling and vocabulary. This general superiority of the Australian sample has been a mark of the data throughout the project. It may relate to ascertainment method—a volunteer twin registry in Australia, approaches based on birth records in the US—with a high degree of self-selection in Australia.

Following standard practice, scores were standardized within country prior to further analysis. They were also age- and gender-adjusted, and outliers were truncated to  $\pm 3 SD$ .

In Table 2 we report the intercorrelations among the measures for the entire sample. The literacy variables (word and nonword reading, reading comprehension, and spelling) intercorrelated quite highly, as is generally found. Their correlations with the vocabulary measure were

somewhat lower, though as might be expected vocabulary was most closely related to reading comprehension. The high correlation between the two subtests of the TOWRE, sight word and nonword reading, a correlation approaching the maximum given the subtests' reliabilities, justified grouping them together into a single variable of word-level reading for some of our subsequent analyses.

### 3.2. Behaviour-genetic analyses

**3.2.1. Grade 2 univariate analyses**—We first report intra-class twin correlations based on the standardized and adjusted Grade 2 scores, separately for country—see Table 3. These data are presented in order to show that (a) the correlations for MZ pairs are consistently higher than for DZ pairs, and (b) there is reasonable consistency across country samples. The Australian and Scandinavian *Ns* are too small to gain sufficient power for stringent modelling of country differences, but when we did compute these models there were no significant differences in the proportions of genetic, shared environment, and nonshared environment influences on each variable as a function of country. Therefore, for further analyses we combined the samples.

As stated, higher monozygotic than dizygotic correlations were observed for each variable, evidence for genetic influence. The data were modelled to estimate genetic (A), shared environment (C), and nonshared environment (E) variance components within the Mx package (Neale et al., 2002). The results are presented in Table 4. Ninety-five percent confidence intervals that contain .00 suggest that the component may not be reliable. The nonshared environment term,  $e^2$ , also includes measurement error. It is clear that the literacy variables are subject to substantial genetic and negligible levels of shared environment influence. Vocabulary is affected by twins' shared environment (home and/or school factors in all likelihood) as well as showing the effects of genetic endowment.

**3.2.2. Grade 2 multivariate analyses**—We next explored the genetic and environmental correlations among word reading (with sight word and nonword subtests amalgamated), reading comprehension, spelling, and vocabulary. Table 5 contains the genetic and nonshared environment correlations, which refer to the degree to which phenotypic correlations are due to genetic and nonshared environmental influences common to a pair of correlated variables. We have omitted shared environment correlations because for three of the four variables the shared environment effect is close to zero; the exception is vocabulary (Table 4). Estimates of these correlations between the measures are obtained from the standardized path coefficients and total heritabilities in a Cholesky decomposition model. For example, the genetic correlation between two variables is a function of the individual heritabilities of the variables and the standardized paths between them.

It can be seen that the genetic correlations among the three literacy measures were high and of very similar magnitude (.83 - .88). In Grade 1, the genetic correlation between word reading and reading comprehension was .97 (Byrne et al., 2007). The Grade 2 value is only marginally lower at .88, indicating that reading comprehension is as dependent, genetically, on word identification as it was a year earlier. Vocabulary, though moderately heritable, was less strongly related to the literacy variables genetically (range, .36 - .62).

The unique environment correlations among the literacy variables were modest (.31 - .42), suggesting unique environmental influence(s) of some breadth. Vocabulary, however, was not subject to the same unique environment effects. Thus it is less tied to literacy, genetically and environmentally, than the components of literacy are tied to each other.

**3.2.3. Longitudinal analyses**—We fitted a Cholesky model that included the preschool traits of print knowledge, phonological awareness, and rapid naming and Grade 2 word reading,

reading comprehension and spelling. In the interests of space, we only table the matrix for genetic factors (Table 6). The shared environment effects on literacy measures at Grade 2 were zero or close to it, and hence of little interest in this longitudinal framework. However, it is worth noting that the small shared environment effects that did emerge for some Grade 2 literacy measures (see Table 5, and ignoring the significance levels) were continuous with the preschool measures—that is, no new shared environment factors were at all in evidence in the Grade 2 phase. This result mirrors one already reported for kindergarten reading, where shared environment effects were “carried” from the preschool phase into school and did not emerge *de novo* in school (Byrne et al., 2005). The unique environment loadings were largely confined to single variables—that is, each of the six variables has a significant unique environment loading but this is not shared with any of the other five variables, again consistent with nonshared environment-as-error.

For both reading and spelling, there is a degree of genetic continuity across the three-year span in a factor (A1) that loads on print and phonological awareness and, to a smaller extent, on rapid naming, as well as on the Grade 2 variables. The genetic factors that loads on phonological awareness (A2) independently of print knowledge does not affect Grade 2 word reading and spelling, though it does load on reading comprehension, with a small value of .25 ( $= .06$  when squared). Factor A3, which captures the genetic variance of rapid naming that is independent of print knowledge and phonological awareness, does affect the Grade 2 variables, with a reasonably substantial loading of .34 ( $= .12$  when squared) on TOWRE word reading efficiency, which shares a speeded task demand with rapid naming. This genetic influence on rapid naming is also significantly associated with the un-speeded task of reading comprehension (loading .22), but not with spelling (loading .15).

New genetic sources in Grade 2 do influence reading and spelling, with factor A4 common to all three literacy variables. Both reading comprehension and spelling are possibly each affected by additional independent genetic sources (A5 and A6, respectively), but with the current sample size those loadings do not reach significance.

The results are similar in some respects to those reported in Byrne et al. (2005, 2006) at kindergarten. For example, phonological awareness, though substantially affected by genes, only related genetically to word reading through genes that it shared with print knowledge. On this occasion at second grade, however, the proportion of the genetic influence on school reading that this common factor (A1) accounted for was .30, computed as  $.25/.82$ , where .25 is the square of the loading on word reading in the model of .50 (Table 6) and .82 is the heritability of the combined word and nonword reading subtests of the TOWRE (Table 4). When kindergarten was the school stage in focus, this value was much higher at .63. Another difference with earlier results is the influence of the “rapid naming genes” (factor A3, Table 6) on word reading (and to a lesser extent, spelling and comprehension). Previously, we had not found that that factor extended its influence into kindergarten reading.

We also computed the longitudinal pattern for vocabulary, using the preschool-administered confrontation naming test, the Hundred Pictures Naming Test, and the Boston Naming Test. The results are presented in Table 7. The modest genetic factor affecting preschool vocabulary, A1, also influenced Grade 2 vocabulary. A second genetic source specific to Grade 2, A2, failed to reach significance. This pattern was mirrored in the shared environment matrix—a significant common source across the time period, C1, and a nonsignificant loading in the second factor, C2. It remains to be seen if with a larger sample these Grade 2 factors assume significance. For the present, genetic and shared environment continuity across the time period, with no new sources coming into play in Grade 2, is the conservative account of the data on vocabulary.



## 4. Discussion

### 4.1. Data summary and interpretations

In this paper we have reported new analyses in an ongoing longitudinal twin study of early literacy growth. We covered Grade 2 performance in word and nonword reading, reading comprehension, spelling and vocabulary. The data are from the fourth testing phase of twin children whose preschool and kindergarten results have been the subjects of earlier publications (Byrne et al., 2002, 2005, 2006, 2007; Samuelsson, Olson, et al., 2007).

Word and nonword reading, reading comprehension, and spelling were substantially heritable. Shared environment effects on these variables were low and nonsignificant, and nonshared environment effects, which include test error, were modest. The word-level reading results continue the trend for substantial genetic effects noted already in the kindergarten and Grade 1 data (Byrne et al., 2005, 2006, 2007), when the heritability values were .70 and .82 respectively (.82 at Grade 2). Shared environment effects, currently non-significant, were in evidence at kindergarten (though not Grade 1), though this was largely driven by the Scandinavian sample (Samuelsson, Byrne, et al. 2008). At the time of our data collection, reading was not expected to be taught in kindergarten in Norway and Sweden, with individual teachers and, independently, parents determining the extent of any literacy instruction. Teachers, schools and homes are sources of environmental variance generally shared by members of a twin pair, so  $c^2$  can be expected to be more substantial under these circumstances. Spelling followed the same pattern as reading, high heritability in Grades 1 and 2, with more shared environment in evidence in kindergarten, particularly in the Scandinavian sample (Samuelsson, Byrne et al., 2008). For both reading and spelling, the etiological patterns fall into line by the end of Grade 1, and, as evidenced by the similar pattern of intra-class correlations across country samples presented in Table 1, this conformity continues into Grade 2.

Reading comprehension was also substantially heritable in Grade 2. It seems likely that our measure of comprehension, the cloze procedure of the Woodcock test, is particularly tied to decoding skill during these early years of school, an observation consistent with other analyses of this test (Keenan, Betjemann, & Roth, 2005). Keenan et al. (2006), also using a twin sample, have further shown that among older school-aged children (mean age 11 years, range 8 – 17 years) listening comprehension makes an independent contribution to reading comprehension after the effects of word-level reading, and further, that it is genes that determine most of the shared variance across all three measures. Thus reading comprehension appears to become less dependent, genetically, on word-level processes as children mature as readers.

The results just summarized reinforce the contention that variability in literacy among people is subject to high levels of genetic influence when educational practices in a society give everyone the opportunity to learn to read and write. Our data are limited to children up to about eight years of age, but results from studies that include a much wider age range show that high heritability continues to hold throughout adolescence (Gayán & Olson, 2003). There is, however, no compelling evidence that reading becomes more heritable as children develop across the age range of this sample. Our kindergarten estimate of heritability was .70 (95% confidence interval of .52 - .93), Grade 1 was .82 (.58 - .86), and Grade 2 was .82 (.67 - .88), all of similar magnitude and with highly overlapping confidence intervals. This lack of increase stands in contrast to other cognitive domains, such as IQ, which are subject to increasing heritability (Bergen, Gardner, & Kendler, 2007; McGue, Bouchard, Iacono, & Lykken, 1993). The high heritability already in place by the end of the first school year apparently leaves little room for further increase.

Vocabulary was similarly affected by genes and shared environment (.45 and .36, respectively). The genetic influence was higher and shared environment lower than when we previously assessed vocabulary in this project in preschool, when values of .19, and .54, respectively, were found, although in the case of genetic influence the confidence intervals at the two phases overlap. For vocabulary, then, our data appear to be more consistent with the observation that shared environment influences on cognitive variables tend to decline and genetic influences tend to increase as children grow older (McGue et al., 1993). Of course, there are many ways to assess vocabulary, and confrontation naming tests are largely restricted to using nouns as items, so these conclusions cannot be generalized with confidence to other forms of vocabulary assessment and other components of the lexicon.

We also add that the genetic influence on vocabulary does not approach that on reading and spelling. In this, vocabulary is on a par with other measures of language that we have collected in our sample; at preschool the heritability of a latent trait comprising tests of morphological and syntactic competence was .29, and in kindergarten the Test for the Reception of Grammar (TROG; Bishop, 1989) was only modestly heritable at .21. Again, generalizing beyond these samples and these tests may be unsound, but the data support the idea that “higher” linguistic processes are less subject to genetic variation than text processing.

The developmental analyses showed that genes that modestly affect print knowledge in preschool ( $a^2 = .21$ ,  $= .46^2$ ; Table 6) continue to affect reading and spelling three years later. The value of preschool letter knowledge, a major component in our print knowledge composite, in predicting subsequent reading growth (Foulin, 2005) may therefore be in part attributable to shared genes and perhaps not directly to some advantage conferred on children who start school with relatively advanced letter knowledge. This claim is consistent with studies that have failed to produce better readers by teaching letter knowledge early (e.g., Samuels, 1972).

As was the case with the preschool-kindergarten progression (Byrne et al., 2005), genetic influences on phonological awareness in preschool that were independent of print knowledge did not continue to play a role in Grade 2 word reading or spelling. However, they did modestly affect reading comprehension; the proportion of variance accounted for was .06 ( $= .25^2$ , Table 6). Thus the genetics of phonological awareness are not coextensive with the genetics of the word-level processes of reading and spelling, but do play a small role in text comprehension. Ramus and Gayaneh (2008) have noted that phonological awareness measures also place demands on working memory, and this may account for its shared genetic link with reading comprehension.

Independent genes affecting rapid naming in preschool affected Grade 2 word reading to a modest extent ( $a^2 = .12$ ,  $= .34^2$ ; Table 5). The loading on reading stands in contrast to the situation holding a year earlier, in Grade 1, which was then close to zero (Byrne et al., 2006). Perhaps the processes that contribute to rapid naming begin to influence reading efficiency with increasing reading experience, not manifest in our sample until the end of the third school year. Both rapid naming and reading as assessed in the TOWRE are timed measures, possibly pointing to speed of mental processing as the common factor.

We identified relatively low levels of shared environment influence on Grade 2 literacy measures. As pointed out in Section 3.2.3, the small effects that we did detect were continuous with preschool shared environment. This suggests that the home environment rather than the school environment is where these effects originate, although if there is selective placement in school as a function of effective aspects of the home environment it is not possible to separate home- from school-based influences. We also add that shared environment effects can be underestimated if genetic effects are not additive. As well, significant if still modest shared

environment effects have been reported in other twin studies (Harlaar et al., 2005; Petrill et al., 2006). Generally, confidence intervals across all these studies overlap, but if the differences are real they may be due to differing samples in differing educational systems and, to some extent, differing measures.

Shared environment played a substantial role in influencing vocabulary variability in Grade 2, as it had in preschool (Table 7). But it is worth noting that this factor was continuous across the age range (the source restricted to the Grade 2 assessment was not significant, but in any case a relatively small contributor to total shared environment). Thus, it also appears to be the home- rather than school-based factors that twins share from which this kind of environmental influence originates, although the caveat about a possible correlation between home and school environments applies here too.

Broadly, our results illustrate the contribution of genetically-sensitive designs to the prediction of school reading levels from measures taken prior to or at the very start of school, an endeavour which incorporates the search for early warning signs of likely reading difficulties (Scarborough, 1998). Prominent among those signs, as determined from phenotypic analyses, are difficulty learning letters, lower than normal levels of phonological awareness, slow vocabulary growth, and other signs of verbal learning deficits (Scarborough, 1998; Snowling, Gallagher, & Frith, 2003). Our data suggest that common genes are the primary source of the predictive power of these indices, with print knowledge as perhaps the signature variable because of its high genetic correlation with school literacy. The data also suggest that phonological awareness achieves most of its predictive power by sharing genes with print knowledge rather than in its own right. In addition, the Grade 2 data indicate that phonological awareness at preschool may be influenced by executive function demands that also affect reading comprehension later in school. Finally, rapid naming, which is highly heritable, comes into the picture when reading skill, also highly heritable, reaches levels where speed of processing matters.

#### 4.2. Underlying biological, cognitive, and behavioural processes

Quantifying genetic influence on aspects of literacy is one thing, identifying the genes and specifying the underlying cognitive and behavioural processes are others. Some progress has been made in the search for genes linked to marked reading disability. In 1983, Smith, Kimberling, Pennington, and Lubs were the first to identify a locus implicated in susceptibility to dyslexia, a region on chromosome 15. In the most recent summary of the genetics of dyslexia, Paracchini, Scerri, and Monaco (2007) report that there are now four genes that have been linked to dyslexia with reasonable reliability (for an earlier summary, see Fisher and DeFries, 2002). The recently identified genes are known as *EKNI* (sometimes as *DYX1C1*) on chromosome 15, *ROBO1* on chromosome 3, and *KIAA0319* and *DCDC2* on chromosome 6 (Paracchini et al., 2007). In one way or another, all of these genes have been shown to have a role in neuronal migration during development. Neuronal migration results in the layered structure of the neocortex, and faults in the process can result in severe disorders like epilepsy. But much remains to be understood about the function of these genes, and it would be premature to conclude that there is anything like a complete picture of the genetics of dyslexia, despite these promising developments. It would be even more premature to conclude that there is a proper understanding of the genetics of variation across the normal range of reading ability, the subject of our investigations. A case can be and has been made for thinking that genes influencing very low levels of performance on a cognitive trait are also genes for normal-range variation, with the likely difference residing in the *number* of adverse alleles that an individual inherits (Plomin & Kovas, 2005). However, there have so far been no direct tests of this hypothesis for literacy.

Although most of our results relate to literacy, we suggest that aspects of our data are of potential interest to neurolinguists whose primary focus is on spoken language. In particular, the finding that language measures typically show modest heritability, as in our estimate of genetic influence on vocabulary of .44 (and earlier estimate for the TROG of .21), reflects the fact that monozygotic twins can sometimes have quite different linguistic profiles (Stromswold, 2006) This in turn means that environmental factors play a substantial role in language variability. As Stromswold argues, this dissimilarity is generally attributed to psychosocial factors that swing into play postnatally but it is plausible that prenatal and epigenetic factors have a role as well. We take just one of the examples that Stromswold supplies. Twins in general, and identical twins in particular, are vulnerable to birthing complications, and may have extended stays in neonatal intensive care. Within a twin pair, these stays can be of different lengths, and because these hospital units are typically noisy and expose neonates to developmentally inappropriate acoustic environments (earlier exposure to high frequency sounds than full-term children), some cases of linguistic delay and twin dissimilarity may begin at this point. Cases of MZ dissimilarity are of particular interest because within-pair differences can only be environmental, or epigenetic. None of our data speak to these particular issues, of course, but the finding of modest language heritability reinforces the need to identify environmental causes of language variation, and twins, especially MZ twins, provide a valuable source of evidence for both biological and social factors that determine levels of linguistic performance.

As for basic cognition, we submit that genetically-affected learning processes play a role in determining rates at which reading and spelling approach mature levels. The data on orthographic learning, with its high genetic correlation with decoding and spelling, were the original basis for this claim (Byrne et al., 2008.) We also suggest that the genetic overlap between preschool print knowledge and school reading levels, reported here and in our earlier articles (e.g., Byrne et al., 2005), supports this account because print knowledge is best characterized as learned associations between graphic and phonological forms. Byrne et al. (2008) were able to demonstrate that the hypothesized genetic factor is substantially independent of genes that affect general intelligence, but more research is needed to further specify its scope—whether it applies, narrowly, to acquiring associations between the structures of print and speech, or has a broader range. We hope to advance this search in future analyses. Whatever the scope of the process, however, one implication is that children burdened by this kind of genetic deficiency will need more exposure to print than other children in order to make the same progress towards mature levels of word recognition skill. Teaching will need to be patient and, critically, thoughtfully structured to maintain motivation to read in the face of slower learning.

A further clue to basic cognitive processes is the well-attested comorbidity between attention deficit and reading disability, which is in part due to shared genes (Willcutt et al., 2002, 2005). This pleiotropic relationship is already in evidence at the preschool stage, where we detected sample-wide genetic correlations in the range of .23 to .36 between inattention and literacy precursors such as phonological awareness and print knowledge (Willcutt et al., 2007). It appears that slow processing speed is the main shared cognitive deficit, at least in the case of attention deficit and marked reading disability (Shanahan et al., 2006). Teaching will need to take account of this slowness if children who are less well resourced genetically are to be brought to mature levels of skill.

### 4.3. Summary

In our Grade 2 sample, literacy levels, including word reading, reading comprehension, and spelling, were genetically influenced to a substantial degree. Vocabulary was subject to moderate influence from genes and from the shared environment. Multivariate analyses

showed that (a) reading comprehension and word reading are affected by the same genes, (b) reading and spelling in Grade 2 are linked genetically to preschool abilities, and (c) genetic sources not present in the preschool measures we have included also affect school literacy.

This project and others like it are advancing our understanding of the course of literacy development, not only by furnishing estimates of the relative influence of genes and aspects of the environment but by delving beneath the quantitative estimates into underlying cognitive, behavioural, and, eventually, biological processes.

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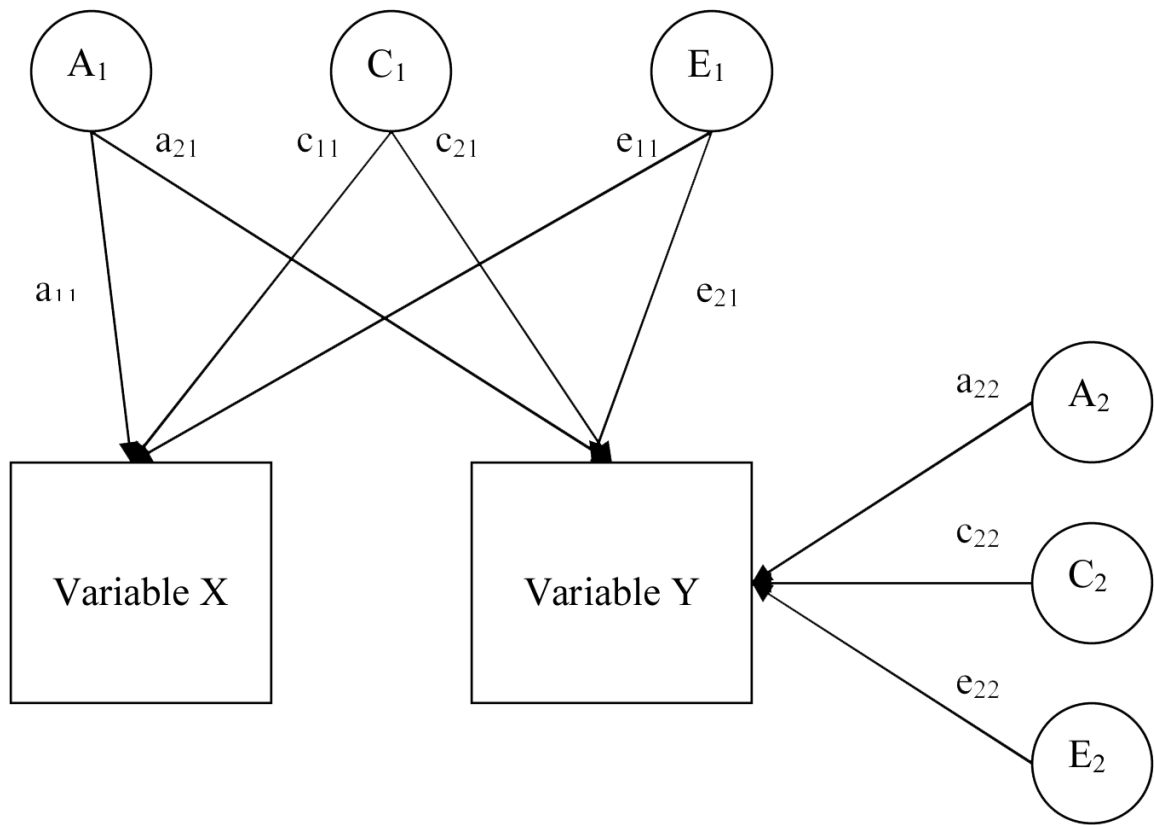
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**Figure 1.**

Cholesky decomposition model shown for one member of a twin pair for two measured variables. Latent variables are represented by circles, measured variable by rectangles. Paths  $a_{11}$ ,  $c_{11}$ , and  $e_{11}$  represent additive genetic, shared environment and unique environment factors that influence Variable X. Paths  $a_{21}$ ,  $c_{21}$ , and  $e_{21}$  represent additive genetic, shared environment and unique environment factors that Variable Y shares with Variable X. Latent variables  $A_2$ ,  $C_2$ , and  $E_2$  represent additive genetic, shared environment and unique environment factors contributing to specific variance in Variable Y after the contributions of  $A_1$ ,  $C_1$ , and  $E_1$  have been taken into account.



**Table 1**

Means (and standard deviations) of Grade 2 measures by country

<i>Measure</i>	<i>US</i>	<i>Australia</i>	<i>Scandinavia</i>
<i>TOWRE SWE</i>	101.97(14.69)	110.47(13.78)	90.23 (15.48)
<i>TOWRE PDE</i>	99.80 (13.87)	110.38(14.50)	98.11 (11.63)
<i>Woodcock Passage Comprehension</i>	100.03 (12.07)	109.75(10.19)	79.90 (12.74)
<i>WRAT Spelling (max. = 45)</i>	17.69(5.78)	18.19(5.84)	24.27(6.13)
<i>Boston Naming Test (max. = 60)</i>	35.65 (5.94)	34.79 (5.78)	34.49 (5.48)

Note: TOWRE = Test of Word Reading Efficiency; SWE= Sight Word Efficiency; PDE = Phonemic Decoding Efficiency; WRAT= Wide Range Achievement Test.

Table 2

## Grade 2 Test Intercorrelations

<i>Test</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
<i>1. TOWRE SWE</i>		.88	.73	.74	.33
<i>2. TOWRE PDE</i>			.69	.77	.30
<i>3. Woodcock Passage Comprehension</i>				.70	.48
<i>4. WRAT Spelling</i>					.32
<i>5. Boston Naming Test</i>					

Note: TOWRE = Test of Word Reading Efficiency; SWE= Sight Word Efficiency; PDE = Phonemic Decoding Efficiency; WRAT= Wide Range Achievement Test.

Table 3

## Intraclass Twin Correlations

Measure	US		Australia		Scandinavia	
	MZ	DZ	MZ	DZ	MZ	DZ
TOWRE SWE	.83	.45	.79	.32	.87	.51
TOWRE PDE	.80	.46	.79	.33	.82	.61
Woodcock Passage Comprehension	.72	.45	.71	.33	.76	.46
WRAT Spelling	.79	.41	.74	.10	.68	.24
Boston Naming Test	.85	.63	.69	.54	.84	.47

Note: TOWRE = Test of Word Reading Efficiency; SWE= Sight Word Efficiency; PDE = Phonemic Decoding Efficiency; WRAT= Wide Range Achievement Test; MZ = monozygotic twins, DZ = dizygotic twins.

**Table 4**

Mx Model Fitting Estimates for Grade 2 Measures (95% Confidence Intervals in Parentheses)

<i>Variable</i>	$a^2$	$c^2$	$e^2$
<i>TOWRE SWE</i>	.84 (.69 - .87)	.00 (.00 - .16)	.16 (.13 - .19)
<i>TOWRE PDE</i>	.74 (.58 - .84)	.07 (.00 - .23)	.19 (.16 - .22)
<i>TOWRE TOTAL</i>	.82 (.67 - .88)	.03 (.00 - .19)	.14 (.12 - .17)
<i>Woodcock Passage Comprehension</i>	.67 (.50 - .78)	.07 (.00 - .23)	.26 (.22 - .31)
<i>WRAT Spelling</i>	.76 (.64 - .80)	.00 (.00 - .11)	.24 (.20 - .28)
<i>Boston Naming Test</i>	.44 (.31 - .59)	.36 (.22 - .49)	.19 (.16 - .23)

Note: TOWRE = Test of Word Reading Efficiency; SWE= Sight Word Efficiency; PDE = Phonemic Decoding Efficiency; WRAT= Wide Range Achievement Test;  $a^2$  = additive genetic variance,  $c^2$  = shared environment variance,  $e^2$  = nonshared environment variance.

**Table 5**

Genetic (above Diagonal) and Nonshared Environment (below Diagonal) Correlations among Grade 2 Literacy Measures and Vocabulary (95% confidence intervals in parentheses)

<i>Variable</i>	<i>TOWRE</i>	<i>Woodcock Passage Comprehension</i>	<i>Spelling</i>	<i>Vocabulary</i>
<i>TOWRE</i>	-	.88 (.83 - .94)	.83 (.78 - .89)	.36 (.20 - .52)
<i>Woodcock Passage Comprehension</i>	.42 (.33 - .51)	-	.84 (.78 - .90)	.46 (.29 - .63)
<i>Spelling</i>	.34 (.24 - .43)	.31 (.21 - .41)	-	.62 (.45 - .79)
<i>Vocabulary</i>	.10 (.00 - .21)	.07 (.00 - .18)	.14 (.03 - .24)	-

Note: TOWRE = Test of Word Reading Efficiency

**Table 6**  
Cholesky Model of Additive Genetic (A) Factor Loadings on Preschool and Grade 2 Variables, (95% Confidence Intervals in Parentheses)

<i>Variable</i>	<i>Factor</i>					
	A1	A2	A3	A4	A5	A6
<i>Print awareness</i>	.46 (.32 - .57)					
<i>Phonological awareness</i>	.44 (.26 - .64)	.55 (.37 - .61)				
<i>Rapid naming</i>	.30 (.07 - .54)	.04 (.00 - .20)	.63 (.38 - .74)			
<i>Word reading</i>	.50 (.31 - .72)	.16 (.00 - .33)	.34 (.05 - .54)	.61 (.42 - .73)		
<i>Reading comprehension</i>	.39 (.19 - .59)	.25 (.01 - .38)	.22 (.03 - .44)	.45 (.26 - .61)	.38 (.00 - .44)	
<i>Spelling</i>	.53 (.34 - .75)	.16 (.00 - .31)	.15 (.00 - .34)	.52 (.30 - .66)	.12 (.00 - .40)	.34 (.00 - .42)

**Table 7**

Cholesky Model of Additive Genetic (A), Shared Environment (c) and Nonshared Environment (E) Factor Loadings on Preschool and Grade 2 Vocabulary, (95% Confidence Intervals in Parentheses)

<i>Variable</i>	<i>Factor</i>	
	<b>A1</b>	<b>A2</b>
<i>Preschool vocabulary</i>	.44 (.30 - .56)	
<i>Grade 2 vocabulary</i>	.60 (.40 - .76)	.28 (.00 - .52)
	<b>C1</b>	<b>C2</b>
<i>Preschool vocabulary</i>	.73 (.65 - .79)	
<i>Grade 2 vocabulary</i>	.52 (.40 - .63)	.31 (.00 - .44)
	<b>E1</b>	<b>E2</b>
<i>Preschool vocabulary</i>	.51 (.48 - .56)	
<i>Grade 2 vocabulary</i>	.06 (.02 - .11)	.43 (.39 - .47)