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Lexical and grammatical development: a behavioural genetic perspective*

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ABSTRACT

The relation of lexical and grammatical knowledge is at the core of many controversies in linguistics and psycholinguistics. Recent empirical findings that the two are highly correlated in early language development have further energized the theoretical debate. Behavioural genetics provides an illuminating new tool to explore this question, by addressing the question of whether the empirical correlation simply reflects the fact that environments which facilitate one aspect of language growth also facilitate the other, or whether the same underlying acquisition mechanisms, influenced by the same genes, are responsible for the correlation. We explored this issue in a study of 2898 pairs of two-year-old twins born in England and Wales. Language development was assessed by their parents using an adapted version of the MacArthur Communicative Development Inventory which assesses vocabulary and grammar. Moderate heritabilities were found for both. As in previous studies, measures of vocabulary and sentence complexity were substantially correlated ($r = 0{\cdot}66$). Behaviour-genetic modelling of the relation of vocabulary and grammar produced an estimated value of 0·61

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for the genetic correlation, a measure of the overlap of the genetic effects that contribute to the two aspects of language development. In contrast, a measure of nonverbal cognitive development, the PARCA, was only weakly correlated at both the phenotypic level and at the level of genetic correlations with the language measures. Thus, although the distinction between verbal and nonverbal skills has a genetic basis underlying the phenotypic dissociation, there is little evidence either genetically or phenotypically for a dissociation between vocabulary and grammar within language.

INTRODUCTION

The relation of lexical and grammatical knowledge is at the core of many controversies in linguistics and psycholinguistics, among them the autonomy of syntax, modularity of mind, the relative utilization of cues in sentence comprehension by adults, and the nature of bootstrapping in language acquisition. Historically the two types of knowledge have been viewed as qualitatively distinct, but in both fields more recently there have been proposals which integrate the two. For example, within linguistic theory there is a chain of development from LEXICAL FUNCTIONAL GRAMMAR (Bresnan, 1982) through CONSTRUCTION GRAMMAR (Goldberg, 1995) and the MINIMALIST PROGRAM (Chomsky, 1995) in which the distinction between grammar and lexicon has steadily disappeared. Within cognitive psychology, many if not most versions of connectionism (Elman, Bates, Johnson, Karmiloff-Smith, Parisi & Plunkett, 1996) posit a single mechanism for both domains.

Recent findings that the two aspects of development are highly correlated in early language development have further energized the theoretical debate (Fenson, Dale, Bates, Reznick, Thal & Pethick, 1994; Bates, Dale & Thal, 1995; Bates & Goodman, 1997). Both the emergence of word combinations and the succeeding development of specific grammatical features appear to be more highly correlated with vocabulary size than with, e.g. age. It is not just that a certain level of vocabulary development is necessary for combinatorial development; based on the large norming sample for the MacArthur Communicative Development Inventories, it is very nearly sufficient as well. As shown in Figure 16 of Fenson *et al.*, 1994, there are almost no cases of children with very large vocabularies who still use minimal, telegraphic speech. Almost never is a large vocabulary found without combinatorial language. Such a finding contrasts strongly with the relation of vocabulary production and comprehension. Though these two skills are related, it is not unusual for a large comprehension vocabulary to be found in conjunction with a small or even nonexistent production vocabulary (compare Figures 14 and 16 of Fenson *et al.*, 1994).

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Several explanations have been offered for this close relation (Bates *et al.*, 1995; Bates & Goodman, 1997). They include the following:

1. A sufficient stock of content words is a necessary foundation for solving the segmentation problem, especially for the perception and identification of unstressed grammatical forms.
2. As children move from learning nouns (primaries, in O'Grady's (1987) logical taxonomy of lexical items) to learning relational words (secondaries: verbs and adjectives) which depend on a relation with one or more primaries to the learning of closed-class words (tertiaries: prepositions, pronouns, conjunctions) which presuppose or depend upon at least one secondary relationship, they are essentially performing the same kind of analysis that is central to grammatical learning.
3. Consistent with lexicalist approaches to grammar, it can be assumed that learning words includes learning their grammatical properties.
4. Early word combinations may in fact be highly lexically specific (Lieven, Pine & Baldwin, 1997), and hence have much in common with vocabulary development.
5. Grammatical knowledge and parsing of input provides important cues for semantic learning (Brown, 1957; Naigles, 1990), e.g. identifying a novel form as a content noun or a transitive verb provides the basis for a hypothesis concerning its meaning.

The first three of these explanations take vocabulary learning to be foundational for grammatical learning, and may collectively be labelled 'lexical bootstrapping.' Explanations 2 and 3 in effect 'upgrade' vocabulary development to resemble grammatical development, whereas Explanation 4 'downgrades' early grammatical development to resemble vocabulary development. In contrast, the fifth assumes an influence in the opposite direction, and has been labelled 'syntactic bootstrapping'(Gleitman, 1990). What all five have in common is an assumption that there is a shared underlying mechanism or mechanisms responsible for both lexical and early grammatical development. Yet there is another, sixth possibility, seldom considered in previous investigations. The empirical correlation between aspects of language development might be just a reflection of the fact that environments which facilitate one aspect of growth also facilitate the other. Research on CHILD-DIRECTED SPEECH and its effects (e.g. Snow & Ferguson, 1977; Tomasello & Farrar, 1986; and Gallaway & Richards, 1994) suggests several possible environmental factors, including total amount of speech, degree of semantic contingency, and frequency of joint attention, each of which could operate to provide better 'data' to functionally distinct lexical and grammatical development processes. The value of the empirical correlation for theorizing would be greatly enhanced if we knew that the same

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acquisition mechanisms, influenced by the same genes, were responsible for the correlations, rather than correlated environmental features

Behavioural genetics thus provides an illuminating new tool to explore these questions. Behavioural genetic techniques such as the twin method are best known among psychologists and other social scientists for investigations of univariate heritabilities, that is, estimating the proportion of variance on a given measure which is due to genetic variation rather than to environmental variation. The fundamental technique is to compare the size of the correlation for identical (monozygotic, or MZ) twins with that for fraternal (dizygotic, or DZ) twins. Monozygotic twins share 100% of their genetic makeup whereas dizygotic twins share on average 50%. To the extent that genetic factors play a role, the former correlation will be higher than the latter. The magnitude of the discrepancy between the two correlations indexes the heritability of the measure, that is, the magnitude of the genetic influence. The effect of shared environmental factors, the factors constituting growing up in the same family, is manifested in the magnitude of correlations for twin pairs regardless of their zygosity. Using these techniques, Dale, Simonoff, Bishop, Eley, Oliver, Price, Purcell, Stevenson & Plomin (1998) recently reported a heritability estimate of 25% for vocabulary size in two-year-olds, based on the same sample studied in the present paper.

The development of multivariate behavioural genetic techniques over the past two decades has constituted a major methodological advance (Martin & Eaves, 1977; Plomin, DeFries, McClearn & Rutter, 1997). These techniques permit an assessment of the influence of genetics and environment on the RELATION between two variables, rather than on a single variable. Like univariate analyses, multivariate analyses contrast correlations for MZ and DZ twins, where the magnitude of the discrepancy indexes a genetic effect, and the magnitude of correlations regardless of zygosity indexes a shared environment effect. But in multivariate analyses, the relevant correlation is that of measure A for twin 1 with measure B for twin 2. Using these techniques, again with the present sample, Price, Eley, Stevenson & Plomin (in press) found that vocabulary and nonverbal cognitive development at age two were moderately related ($r = 0{\cdot}42$), but that this correlation was primarily due to common effects of environment rather than to shared genetic influences (genetic correlation of 0·3, shared environment correlation of 0·51, as explained below). Price *et al.* did not examine the relations among other aspects of language development or their relation to nonverbal cognitive development.

As discussed above, the empirical correlation between aspects of language development may reflect the fact that environments which facilitate one aspect of growth also facilitate the other. Alternatively, the same underlying acquisition mechanisms, influenced by the same genes, may be responsible for the correlations. In the present study, we examined the relation between

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vocabulary and grammatical development at age 2. Two years is a particularly appropriate age to study individual differences in language development because it follows a period of rapid acceleration in the acquisition of words in the second half of the second year of life, and the beginning use of word combinations by most children before this age. Furthermore, it is the period in which the close relation between lexical and grammatical development has been most clearly demonstrated (Bates *et al.*, 1995). We also included a measure of nonverbal cognitive development, in order to assess the specificity of the relations among language measures.

The goals of the present investigation were

1. To explore etiological issues in language development at two years with a large sample of twins by estimating the roles of genes and environment in lexical and grammatical development individually, and to compare them;
2. To replicate previous findings of a close empirical (phenotypic) relation between lexical and grammatical development;
3. To evaluate the contribution of genes and environment to the correlation between these aspects of early language development; and
4. To evaluate the specificity of the link between language measures in relation to other aspects of cognitive functioning early in development.

METHOD

The sample for this investigation consisted of a subgroup of twins recruited for the TWINS EARLY DEVELOPMENTAL STUDY (TEDS) in England and Wales. Through the U.K. Office for National Statistics, parents of twins born in 1994 were initially contacted to take part in the study. Of 7756 families contacted after excluding for infant mortality at year one, 4688 returned the completed booklet sent out to gather background information. A subsequent booklet was sent out shortly before the twins' second birthday to assess various developmental milestones separately for each twin. Of the families that had returned the background booklet, 3442 returned the completed two-year booklets.

The representativeness of this subgroup was assessed with two types of comparison. First, the sample was compared to 1994 U.K. census data to assess representativeness in terms of maternal ethnicity and education. Though mothers of the twin sample were slightly better educated, 34% of them achieving at least an 'A level' (analogous to successful high school completion) as compared to 32% in the census data, and 94% self-described as 'white' compared to 92% in the census data, the differences remain modest. Second, families that returned the second booklets and those that did not were compared. There were no substantial differences between the two groups on maternal age, ethnicity, marital status, parental educational levels

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or employment (see Dale *et al.*, 1998, for more information on this comparison).

The sample was further reduced by 544 pairs for the analyses conducted in this investigation following the exclusion criteria described in Dale *et al.* (1998) and summarized here. Zygosity of same-sex twin pairs, whether they are identical (monozygotic, or MZ) twins, or fraternal (dizygotic, or DZ) twins, was assessed through a parent-rated questionnaire. Successful assignment of zygosity was achieved for 95% of the sample, a rate comparable to other twin studies (Goldsmith, 1991), thus omitting 70 pairs from subsequent analyses. Accuracy of the zygosity assignment was verified for a random sample of 68 pairs with DNA testing, confirming a 96% accuracy rate for the parent-rated zygosity instrument. This accuracy rate is also comparable to other twin studies (Plomin *et al.*, 1997). An additional 119 pairs for whom the two-year booklets were returned or completed more than six months after the children's second birthday were excluded from subsequent analyses. Though analyses control for age effects, the rapid rate of language development in the preschool years warrants limiting the age range for completion of the booklets. Constraining that age range to be within three months of the twins' second birthday yielded very similar results to the six-month threshold criteria so the six-month criteria was retained. Another 87 pairs were excluded to control for medical and extreme perinatal problems associated with problems in language development. Of these, pairs where at least one twin had a hearing problem, a specific medical condition such as cystic fibrosis or cerebral palsy or chromosomal anomaly such as Down's syndrome accounted for 41 exclusions; 46 pairs were discounted for being extreme outliers on measures of birthweight, gestational age, time spent in the hospital and need of special care after birth as well as maternal alcohol consumption during pregnancy. The remaining exclusions are accounted for by 116 pairs for whom English was not the first language spoken in the home and 152 pairs where one twin did not have a valid score for all language scales used in the analyses. The final sample was composed of 2898 twin pairs: 1008 MZ pairs, 959 same-sex DZ pairs and 931 opposite-sex DZ pairs. The mean age of this sample was 2;0.17 ($\pm$0;0.17 standard deviation) at time of completion of the second booklets.

Measures

The two-year booklet mailed to parents included an adaptation of the MacArthur Communicative Development Inventory: Words and Sentences (MCDI; Fenson *et al.*, 1994). Using the MCDI, parents report on their children's production of root words, a vocabulary measure, whether their children are combining words, and the complexity of their children's multiword sentences; the latter two provide measures of grammatical development. The MCDI has been widely used in studies of early language

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development and has been demonstrated to show excellent internal consistency and test-retest reliability as well as concurrent validity as measured by correlations with tester-administered measures (Fenson *et al.*, 1994). For this study, abridged versions of the vocabulary and the grammar scales were used. These short forms have the double advantage of being cost effective for such a large sample study while still offering a valid measure of distinct aspects of early linguistic development. (Other questions included in the adapted MCDI are not reported in this paper.) All components of the language questionnaire included minor modifications to 'anglicize' the instrument for the U.K. setting; for this reason the instrument will be referred to as the MCDI:UKSF, for 'UK short form.' In addition to the MCDI:UKSF, the two year booklet also contained a measure of nonverbal aspects of cognitive development. This measure, described below, was included in order to evaluate the specificity of the relation among the language measures.

Assessment of vocabulary production. The 100-word short form vocabulary scale of the MCDI:UKSF used in this study is one of two such condensed lists that predicts the full 680 word version of the MCDI with very high accuracy (r = 0·98) (Fenson, Pethick, Renda, Cox, Dale & Reznick, 2000). Parents are asked to check off the words on this list they have heard their children say. A composite is calculated by adding up the number of words checked. One of these lists (Form A), with a few minor changes to include culturally appropriate vocabulary for a British sample, constituted the vocabulary scale.

Assessment of grammar. The MCDI:UKSF sentence complexity scale is comprised of 13 questions pertaining to children's grammatical ability. The first question assesses whether the child is able to combine words (yes scores 1). The remaining 12 items present two sentences carrying the same meaning, the first representing a developmentally simpler form, e.g. baby crying vs. baby is crying. Parents are asked to check the sentence in each pair that most resembles what they have heard their child say. A point is awarded for each pair in which the parent selects the more complex sentence. The selection of 12 sentence pairs from the full set of 37 in the original scale was made on the basis of range of difficulty and internal consistency analyses.

Assessment of nonverbal cognitive abilities. The two year assessment booklet so included a newly devised measure of nonverbal (performance) cognitive abilities, the Parent Report of Children's Abilities (PARCA). This measure, described more fully in Saudino, Dale, Oliver, Petrill, Richardson, Rutter, Simonoff, Stevenson & Plomin (1998), consists of both parent-report questions (e.g. ''Does your child recognize himself/herself when looking in

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a mirror?'') and parent-administered items (e.g. copying a design, building with blocks). Using PARCA scores and the vocabulary and grammar measures described above (the grammar measure in its original, 13-point version) with a sample of 107 2-year-olds, Saudino *et al.* found a multiple correlation of $R = 0{\cdot}66$ with the Mental Development Index (MDI) of the Bayley Scales of Infant Development-II administered two weeks later. This ability of parent-based assessments to predict the MDI is comparable to the predictive power of other tester-administered standardized tests.

RESULTS

Lexical and grammatical development at age two in twins

There is a wide variability of vocabulary production at age two for this sample. Although 28 children could not produce any recognizable word, 146 children could produce all the words on the list by age two. The mean of 48 ± 25 (standard deviation) words for this sample represents a three-and-a-half-month delay compared to results on a U.S. sample of singletons (Fenson *et al.*, in press). This language production delay in twins is consistent with other research on twin language development (Rutter & Redshaw, 1991).

The grammar scale showed much less variability at age two for this sample. A substantial proportion of twins were reported as not yet combining words at this age, and very few had advanced into the aspects of morphology and early syntax assessed by the sentence pairs. The scale mean is $1{\cdot}8 \pm 2{\cdot}5$ (standard deviation), with 1838 children scoring a total of 0 while very few were able to utter the more complex sentences in the list (34 children scoring the maximum of 12). For this reason, and to produce a more normally distributed score appropriate for variance analyses, a new sentence complexity composite score was calculated by recoding the original scale into a three point scale: unable to combine words yet (score 0), able to combine words but only in the simpler form of the given sentences (score 1) and able to use at least one of the more complex forms of sentences (score 2). For this new scale, used in all further analyses, the distribution was approximately rectangular, with a mean of $0{\cdot}96 \pm 0{\cdot}77$ (standard deviation).

Table 1 shows the sample sizes, means and standard deviations for the total sample and subgroups of the sample on the vocabulary scale and the three-point sentence complexity (grammar) scale.

For the total sample, ANOVAs performed for zygosity (the effects of being identical (MZ) versus fraternal (DZ) twins) and sex effects showed slight but significant main effects as well as an interaction effect where girls and fraternal (DZ) twins are favored. Similar results favoring girls in rate of language development have been observed in other research (Butterworth & Morissette, 1996; Huttenlocher, Haight, Bryk, Seltzer & Lyons, 1991), including studies using the MCDI (Fenson *et al.*, 1994). The etiology of

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TABLE 1. *Sample size and MCDI Vocabulary and Grammar raw score means and standard deviations (S.D.) for the total sample by zygosity and sex*

		Vocabulary		Grammar	
	N	Mean	S.D.	Mean	S.D.
Total sample	5796	47·56	24·78	0·96	0·77
MZ twins	2016	46·01	25·10	0·93	0·77
DZ twins (excl. opp.-sex)	1918	48·36	24·42	0·96	0·77
MZ females	1084	50·67	24·45	1·08	0·77
MZ males	932	40·59	24·76	0·76	0·73
DZ females	948	53·26	24·13	1·11	0·77
DZ males	970	43·57	23·75	0·83	0·75
Opposite-sex DZ twins	1862	48·41	24·74	0·99	0·77

Zygosity × sex ANOVAs for the total sample indicate significant zygosity ($p < 0·001$), sex ($p < 0·0001$) and zygosity × sex interaction ($p < 0·001$) for both scales.

TABLE 2. *MCDI Vocabulary, Grammar, and PARCA phenotypic correlations*

	Vocabulary	Grammar	PARCA
Vocabulary	1·00		
Grammar	0·66*	1·00	
PARCA	0·41*	0·32*	1·00

* $p < 0·0001$.

these modest gender differences in the present sample is explored in Galsworthy, Dionne, Dale & Plomin (2000). Though age correlates only 0·16 with vocabulary scores and 0·14 with the three-unit sentence complexity, scores were residualized by regressing them on age and sex as is customary in developmental twin research to avoid unduly inflating twin similarity (McGue & Bouchard, 1984).

The relation of vocabulary and grammar at two years

Table 2 presents the intercorrelations for vocabulary, grammar and the non-verbal cognitive measure. The language measures measures show a high phenotypic intercorrelation (0·66). In contrast, the correlations between each language measure and the non-verbal cognitive measure PARCA are modest, 0·41 and 0·32 for vocabulary and grammar, respectively.

Because the correlation coefficient measures the strength of a linear assocation, it can actually underestimate an association which is nonlinear. For this reason, Figure 1 provides a more precise account of the relation of vocabulary and the onset of grammar, by plotting the emergence of word combinations against vocabulary. The sharp rise in combinations occurring

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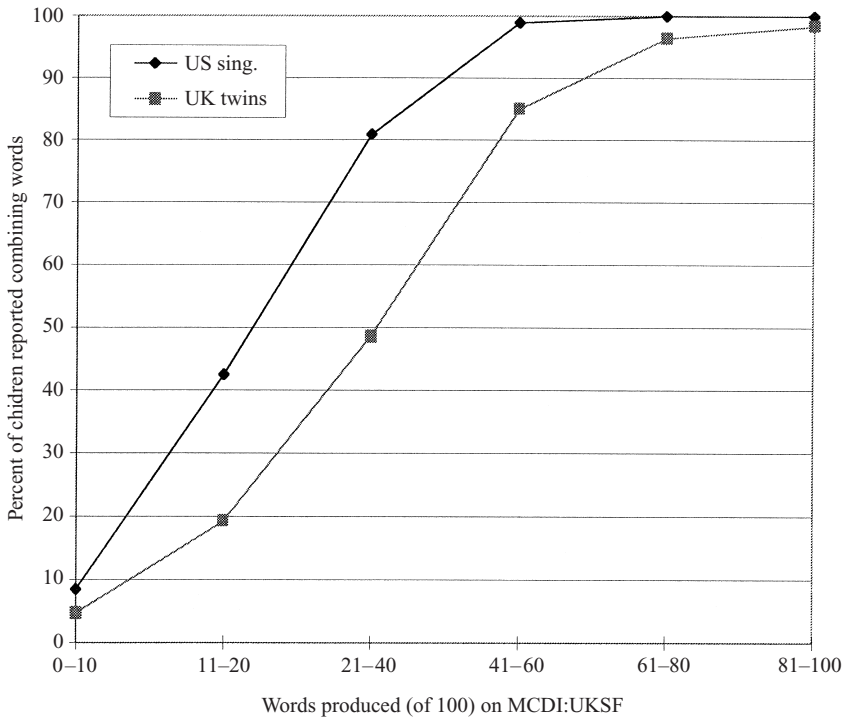


Fig. 1. Proportion of twins and singletons combining words as a function of expressive vocabulary.

around 21–40 words is a good example of a strong nonlinear association. Figure 1 also includes comparable data from Fenson *et al.* (in press) for comparison. As shown in the previous section, both vocabulary and grammar are somewhat delayed in two-year-old twins, but there is still a close relation between them. Interestingly, vocabulary appears to reach a somewhat larger size in twins than singletons before combinations are produced.

The substantial correlations are consistent with the view that these aspects of language emerge in an integrated fashion and are somewhat distinct from non-verbal cognitive development at this early stage. But as discussed earlier, to characterize the underlying cause of this pattern of intercorrelations, genetic analyses are appropriate. These analyses were conducted in two phases, reported in the sections below. First, univariate genetic modelling was used to characterize the etiology of each language aspect separately in terms of genetic and environmental influences. Subsequently, multivariate genetic modelling addressed the genetic and environmental origins of the covariation between these aspects of language development as well as the specificity of the etiology of language aspects early in development.

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Univariate behavioural genetic analyses of vocabulary and grammar development

The goal of univariate analyses of the vocabulary and grammar scales is to estimate the proportion of variance for each scale due to genetic, shared environment and nonshared environment factors. A first approximation of these variance components can be obtained by simply comparing intraclass correlations for MZ and DZ twins. Figure 2 illustrates the intraclass correlations for MZ, same-sex and opposite-sex DZ twin pairs for vocabulary and grammar scores. For both measures, the highest correlation is for MZ twins; the DZ correlations are both lower, but with a relatively small difference between same-sex and opposite-sex pairs. The greater the difference between MZ and DZ intraclass correlations for a trait, the higher the heritability. Heritability can be estimated approximately as twice the MZ–DZ correlation difference (Plomin *et al*., 1997). The shared environment variance component can be approximated by subtracting twice the MZ–DZ correlation difference from the MZ correlation. The logic of this calculation is that the MZ correlations should be twice as high as the DZ correlations when this difference is accounted for entirely by genetic dissimilarity across zygosity groups (DZ genetic similarity being half of MZ genetic similarity). The shared environment variance component will reflect the extent to which the correlations depart from this theoretical expectation, due to similarity between twins beyond that accounted for by genetic similarity. The remaining variance approximates the nonshared environment variance component, that is, the proportion of variance that cannot be accounted for by the genetic relation of a twin pair nor by the fact that they are growing up in the same family. Thus, the twin correlations in Figure 2 indicate moderate genetic influence and substantial influence of shared environment for both measures.

Statistical genetic modelling of twin data provides a more comprehensive way of estimating variance components based on the same principles. Such genetic modelling of data is based on structural equation modelling where path coefficients are estimated for latent factors linked to an observed variable. From observed covariance matrices calculated separately for MZ and DZ twins, and a specified variance/covariance model, maximum likelihood parameter estimates are computed that best fit both the observed covariance matrices and the provided variance equations. In the variance/covariance equations provided for the model fitting, the total variance for MZ twins will be equal to the additive effects of genes, denoted here as G, shared environment, denoted as C, and nonshared environment components, denoted as E. The variance equation for DZ twins will be equal to half the additive genetic component added to the shared and nonshared environment components. Univariate genetic model fitting estimates for vocabulary and

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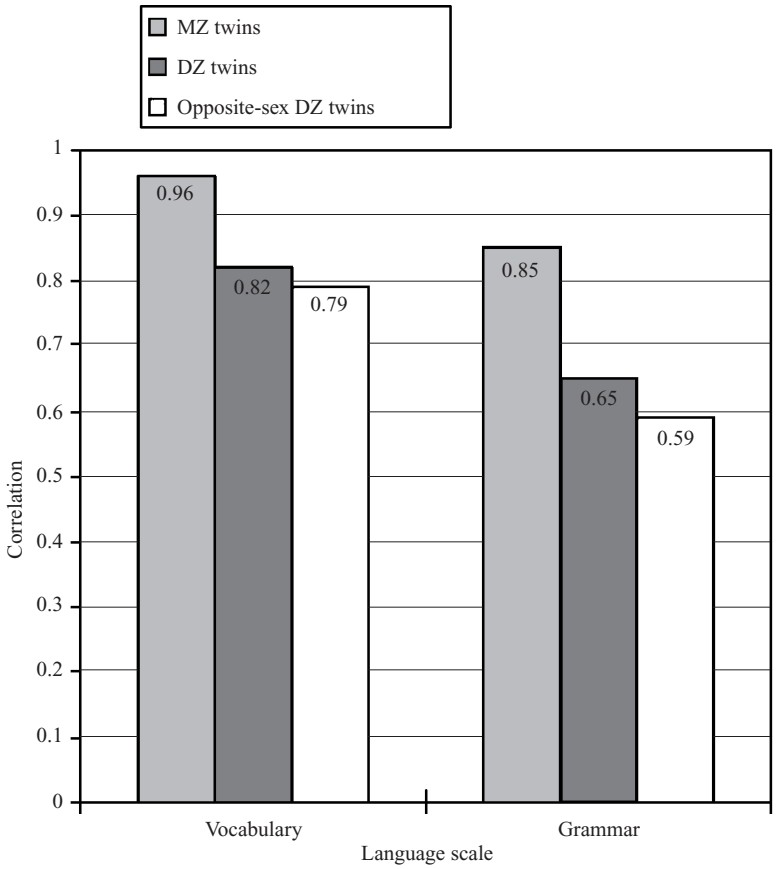


Fig. 2. MCDI Vocabulary and Grammar intraclass correlations by zygosity.

sentence complexity are presented in Table 3. In each case, the model offered a reasonably good fit by the standard statistical criteria, including a non-significant chi-square. The fit for the grammatical development measure was somewhat less adequate than for the vocabulary measure.

Moderate heritabilities are found for both language scales. Genetic factors explain 25% (21–28 CI) of the variance on vocabulary scores and 39% (33–46 CI) of the variance on sentence complexity scores. The greater proportion of the variance for both language measures is explained by shared environment factors: 69% (65–72 CI) for vocabulary and 48% (41–53 CI) for sentence complexity. Thus some additive genetic factors are linked to lexical and grammatical development individually, but the majority of the influences for each remain linked to family environment. These results are similar to those reported by Reznick and colleagues (Reznick, Corley &

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TABLE 3. *Univariate genetic model fitting estimates and criteria for MCDI Vocabulary and Grammar scales*[a]

	Vocabulary	Grammar
G (g^2)	0·25	0·39
	(0·21–0·28)*	(0·33–0·46)*
C (c^2)	0·69	0·48
	(0·65–0·72)*	(0·41–0·53)*
E (e^2)	0·07	0·13
	(0·06–0·07)*	(0·12–0·15)*
Fitting criteria		
AIC	−4·85	
RMSEA	0·000	
χ^2	1·15	
D.F.	3	
p	0·764	

* 95% confidence intervals.
[a] G = additive effect of genes; C = effect of shared environment; E = effect of nonshared environment.

Robinson, 1997) in a recent genetic study of a parent-report language measure on two-year-old twins.

It should be noted that any influence that contributes to making the scores of twins more similar than they are in reality, such as a failure on the part of parents to fully discriminate the development of their twins will inflate the shared environment estimate. It is also possible that parents rate one twin by contrast with the other, thus making their scores more different than they are. The effect of such a contrast effect will be nested in the nonshared environment effect. Such contrasts have been noted for personality ratings of twins by parents (Saudino & Cherny, in press), but are unlikely in the present case because the nonshared environment component of variance is so small. Moreover, a comparison of the vocabulary parent report measure with a parent report and a parent administered measure for the cognitive scales for the present sample suggested that these biases were minimal for these measures (Price *et al.*, in press).

Multivariate modelling of the relation between vocabulary and grammar development

To address the theoretical question at the core of this paper, the sources of covariation between vocabulary and grammatical development, multivariate genetic models were fitted. The basic principle is analogous to that used in univariate modelling, with the exception that it is the correlation between the

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two measures that is the focus. A model is fitted on the basis of comparisons of cross-trait correlations between pairs of measures as a function of the genetic similarity of the twins (MZ versus DZ). The cross-twin correlation is a measure of how scores for twin 1 on measure 1 vary in comparison to scores of twin 2 on measure 2, where twins 1 and 2 refer to a twin pair. In the present sample, the cross-twin correlation for vocabulary and grammar was 0·64 for MZ twins and 0·51 for DZ. The lower value for DZ suggests a genetic component to the correlation. Just as doubling the difference in MZ and DZ correlations approximates the degree of heritability in univariate analyses, doubling the difference in MZ and DZ cross-trait twin correlations provides a rough estimate of the degree of genetic influence on the phenotypic correlation. Doubling the MZ–DZ difference in cross-trait twin correlation for vocabulary and grammar ($0{\cdot}64–0{\cdot}51 = 0{\cdot}13 \times 2 = 0{\cdot}26$) suggests that about 40% of the phenotypic correlation between vocabulary and grammar is mediated genetically ($0{\cdot}26 = 39\%$ of the phenotypic correlation 0·66).

Multivariate modelling of the relation between vocabulary and grammar provides a decomposition of variance and covariance based on a theoretical model of latent and observed variables. The analysis is done in two steps. First, the Cholesky decomposition technique was used to fit the model shown in Figure 3. Like hierarchical multiple regression, this analysis is based on a

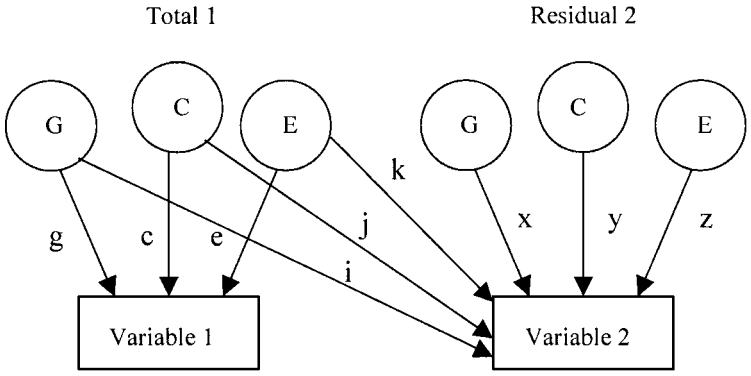


Fig. 3. Path diagram depicting the bivariate Cholesky decomposition of two variables. Additive genetic (G), shared environment (C) and nonshared environment (E) estimates are derived for each variable; in addition: g^2 = heritability for variable 1 and i^2+x^2 = heritability for variable 2; genetic correlation $r_G = i/\sqrt{(\text{heritability for variable 2})} = i/\sqrt{(i^2+x^2)}$; $gi/gi+cj+ek$ = bivariate heritability (proportion of covariance explained by genetic factors); $g^2+c^2+e^2$ = total variance for variable 1 (Total 1); $i^2+j^2+k^2$ = partial variance for variable 2 explained by variable 1 factors (Partial 2); $x^2+y^2+z^2$ = residual variance for variable 2 (Residual 2); Partial 2 + Residual 2 = total variance for variable 2 (Total 2); Total variance for each variable is constrained to 1.

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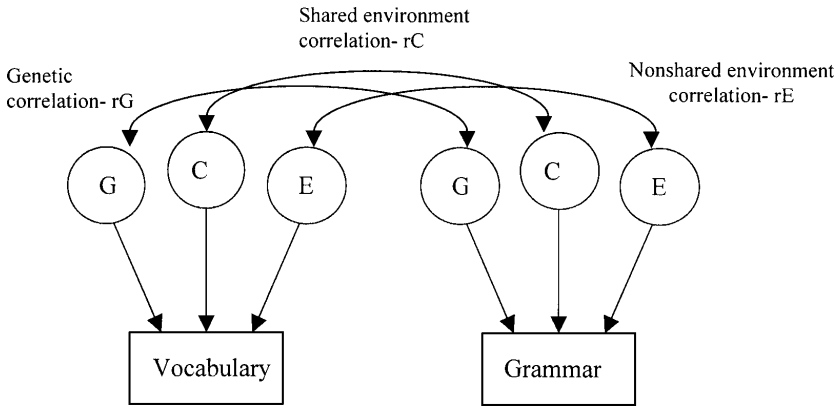


Fig. 4. Path diagram depicting the correlated factors model where r_G represents additive genetic correlation, r_C the shared environment correlation and r_E the nonshared environment correlation between variable 1 (Vocabulary) and variable 2 (Grammar). Additive genetic (G), shared environment (C) and nonshared environment (E) estimates are derived for each variable.

TABLE 4. *Proportion of phenotypic correlation (covariance) explained by each variance component, factor correlations and model fitting criteria for multivariate genetic model*

	Vocabulary and Grammar
Genes	28%
Shared environment	69%
Nonshared environment	3%
r_G (genetic correlation)	0·61
r_C	0·74
r_E	0·25
Fitting criteria for the 2-way multivariate model	
AIC	−6·906
RMSEA	0·012
χ^2	15·094
D.F.	11
p	0·178

specific sequence of variables. When there is no rationally defined basis for sequencing, such as temporal order or a specific causal model, it is more appropriate to transform the results of the Cholesky decomposition model into parameter estimates for the correlated factors model shown in Figure 4 (Loehlin, 1996). This transformation was performed in the present analysis, due to the lack of a strong *a priori* basis for ordering vocabulary and

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grammar. The correlated factors model provides information on etiological issues at two levels, each represented by a different type of statistic. The two levels provide different insights into the sources of covariation between variables. First, the model provides estimates of the proportion of the phenotypic covariance which is due to genetic, shared environment, and nonshared environment factors. The proportion which is due to genetic factors has been labelled 'bivariate heritability.' The formula for its computation is provided in the legend for Figure 3. One important difference between univariate heritability and bivariate heritability is that the former has a theoretical maximum value of 1·0, based on a possible correlation of 1·0 between MZ twins if variation on that trait is entirely accounted for by genetic factors. In contrast, bivariate heritability is limited by the phenotypic correlation between the two measures. This is because even if all the covariance is accounted for by genetic factors, the highest possible cross-trait correlation for MZ twins is the phenotypic correlation. In effect, the MZ and DZ cross-trait correlations should be compared with the phenotypic correlation, rather than to 1·0 as in univariate analyses. Second, the model assesses the extent to which the two variables are influenced by the same genetic factors (the genetic correlation r_G), independent of the heritability of the two traits. Computationally, the genetic correlation is the genetic contribution to the phenotypic correlation divided by the product of the square root of the product of both univariate heritabilities. As noted above, a rough estimate of the genetic contribution to the phenotypic correlation is 0·26, which suggests a very substantial value for the genetic correlation ($0{\cdot}26/\sqrt{(0{\cdot}25 \times 0{\cdot}39)} = 0{\cdot}26/0{\cdot}31 = 0{\cdot}84$). The model also estimates the shared environment correlation (r_C) and the nonshared environment correlation (r_E). Note that all three statistics range between zero and one, as they are measures of overlap. Genetic correlation and bivariate heritability provide different information concerning the genetic links between variables. For example, the genetic correlation between vocabulary and grammar could be very high, indicating the genetic effects on the two domains overlap substantially, whereas the bivariate heritability could be low because the heritability of one or both of the domains is low.

As Table 2 illustrated earlier, the measures of vocabulary and grammar are substantially correlated phenotypically. Table 4 presents the results of multivariate genetic modelling of these relations, including both types of indices discussed in the previous paragraph. First, it presents the proportion of the phenotypic correlation between vocabulary and grammar that is explained by genetic, shared environment and nonshared environment effects. The bivariate heritability value indicates that about a quarter (28%) of the phenotypic correlation is mediated genetically. Most of the phenotypic correlation between these measures is explained by shared environment effects. These results are quite similar to the results of the univariate

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analyses, which revealed moderate heritabilities for the measures considered singly.

Second, Table 4 also summarizes analyses of the covariation between lexical and grammatical development with respect to the proportion of overlap between variance components. As discussed earlier, the genetic, shared environment, and nonshared environment correlations assess the overlap between the respective factors that influence this pair of language scales.

Although bivariate heritability is moderate to low between vocabulary and grammar, the genetic correlation is quite high (0·61), indicating a substantial overlap in genes that influence the two. That is, although genetic factors contribute at a moderate to low level to each of these aspects of early language development considered individually, they are for the most part the same genetic factors. Less surprisingly, the shared environment correlations is also quite high (0·74) indicating a substantial overlap between the family environment factors influencing both aspects of language.

The specificity of the links among language measures

The specificity of the link between vocabulary and grammar as language measures in relation to general cognitive development can be assessed at two levels. The first is the comparison of the phenotypic correlations between the two language measures and the PARCA with the correlation between the language measures. As shown in Table 2 earlier, the language measures are substantially more correlated between themselves than either of them correlates with the PARCA. The second level is the comparison of the genetic, shared environment, and nonshared environment correlations among the measures, based on the result of bivariate model-fitting for the PARCA and each of the language measures. Price *et al*. (in press) examined the relation of vocabulary and PARCA scores, and concluded that these abilities are largely independent at this early stage of development; the bivariate heritability for the two measures is just 0·17 and the genetic correlation (r_G) is only 0·30.

In the present study, we performed similar analyses for the grammar measure as well as for vocabulary. Table 5 summarizes the results of these

TABLE 5. *Proportion of total variance explained by PARCA variance factors, residual variance and genetic factor correlations for bivariate genetic models of PARCA with Vocabulary and Grammar*

	Vocabulary	Grammar
Explained by PARCA	20·7 %	10·6 %
Residual variance	79·3 %	89·4 %
r_G (genetic correlation)	0·34	0·29

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analyses. Note that in this case, the hypothesis that the language results are a reflection of broader cognitive factors does imply a specific sequencing of variables, namely, a theoretically based ordering of cognition before language. Thus Table 5 includes information on the residuals from the initial Cholesky decomposition technique (Figure 3) as well as the genetic correlations from the correlated factors model (Figure 4; note that the caption for Figure 3 includes the computational formulas for the relevant indices). PARCA scores account for even less of the variance of grammar scores than they do for vocabulary. PARCA variance components explained only 10·6% of the variance in grammar scores ($r_G = 0{\cdot}29$). (The results for the PARCA and vocabulary measures differ slightly from those reported by Price *et al.* since slightly more cases were omitted in the present analysis due to the need for complete data on all measures.) The modest genetic correlations between PARCA and both language scales and the high residual variances suggest that language development is relatively independent of non-verbal cognitive development at this early age.

DISCUSSION

Parent report and the language development of twins

Fundamental to the present study was a methodological issue that has not previously been addressed: can parents of twins provide valid information on the language development of their children individually? Divided attention between the children, similarity on other dimensions of personality and appearance, and the undoubted stress of caring for two young children might all be expected to diminish the validity of parent report as a research tool for twins. Nevertheless, on the whole parent report appears to be reasonably valid. Saudino *et al.* (1998) correlated the present parent report measure of vocabulary with a tester-administered measure (the language portion of the Bayley Scales of Infant Development) for a sample of twins and triplets; the resulting correlation (0·58) was similar to that reported in Dale, Bates, Reznick & Morisset (1989) for the 'Seattle Fullterm' sample of non-twin siblings (0·59) using the Early Language Inventory, a precursor of the present vocabulary measure. In the present study, parent report measures yielded a coherent and interpretable set of results, such as higher correlations for MZ than DZ twins, modest delay on both language measures as compared to singleton norms, and higher correlation between the two language measures than between language and the nonverbal measure, a pattern which provides additional support for the measures. Furthermore, the moderate univariate heritabilities found here are comparable to those estimated by Reznick *et al.* (1997) on the basis of a tester-administered measure. This last finding is particularly notable, because an inability to discriminate the abilities of two children should lead to substantially lower heritability. Thus,

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parents appear to be able to discriminate distinct aspects of development AND their two children. Nevertheless, the most convincing evidence that parent report provides valid information for behavioural genetic purposes – a demonstration that correlations between parent report and other measures are similar for MZ and DZ twins – is still not available.

The present sample is by far the largest dataset on language development in young twins. On the vocabulary scale, the sample demonstrated a delay of 3–4 months. No singleton norms are available for the particular shortform grammar scale used here. However, in the MCDI norming study (Fenson *et al.*, 1994), by 1;6–1;8 60% of toddlers were reported to be combining words, whereas a bit more than half were combining in the present two-year sample, which suggests a slightly larger delay for combining words than for vocabulary. It is not difficult to suggest environmental reasons for delay in language development. Although parents may speak as often to twins as to singletons, their ability to establish joint reference, to provide semantically contingent responses, and to monitor each child's comprehension – aspects of child-directed speech that appear to be particularly facilitative of language development – are all inevitably reduced by the need to interact with two young children at a time. In the only published study of input to twins, Tomasello, Mannle & Kruger (1986) observed six twin pairs (all firstborn) at 1;3 and again at 1;9, and noted that in comparison with firstborn singletons, the twins received less speech and participated in fewer and shorter episodes of joint attentional focus. Their mothers's speech was also more directive. Correlational analyses suggested that environmental factors were related to rate of early language growth. Studies of older twins generally find language to be in the normal range (e.g. Bishop, Bishop, Bright, James, Delaney & Tallal, 1999), but longitudinal studies of this 'catch-up' would be valuable.

The finding, illustrated in Figure 1, that a larger vocabulary is established in twins prior to combining words than for singletons, also merits additional research. It is possible that the shortform vocabulary list used here is less appropriate for U.K. twins than for U.S. singletons as an index of total vocabulary. Alternatively, parents may notice word combinations less promptly for twins than for singletons. Yet another interpretation is that it is not the total vocabulary, but the emerging subset of verbs and adjectives that predicts word combinations. Twins may learn more nouns than verbs and adjectives, an hypothesis which is directly testable with a more complete vocabulary checklist.

The use of the twin method may be questioned on the grounds that twinship itself affects the rate of language development. However, as Table 1 shows, identical (MZ) and fraternal (DZ) twins are quite comparable in overall score and hence in developmental lag. Thus the internal logic of the twin method should remain intact, because it compares the resemblance of

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the two types of twins. However, it may affect the generalizability of the conclusions of this study to the singleton population which does not experience those environmental features which contribute to the lag. For this reason we are obtaining measures on the younger siblings of the twins in order to include twin–sibling comparisons in quantitative genetic analyses.

Genetic influences on lexical and grammatical development

Univariate genetic analyses of these two dimensions of language growth yielded a relatively consistent set of results: there are moderate genetic effects for each (modestly larger for grammar), and far larger shared environment effects. These results refer to individual differences throughout the normal range of variation in our sample. Quite different patterns can obtain at the extremes. An analysis of influences on children in this sample whose vocabulary scores were in the lowest 5% found high heritability (73%) for delay, in contrast to the moderate heritability found across the entire range (Dale *et al.*, 1998).

The univariate heritabilities for vocabulary and grammatical development obtained in the present study are somewhat discrepant from those reported in another recent study. Ganger, Pinker, Baker & Chawla (1998) studied 76 twin pairs longitudinally with a variety of parent-based techniques. Because their study was longitudinal, it was possible to use the age at which children reached significant milestones (first 10, 50, and 100 words, and first combinations) as the dependent measures, rather than level of development at a specific age (2;0) as in the present study. However, both studies were focussed on comparable early levels of development. Ganger *et al.* obtained very low heritabilities for vocabulary −9%, 1%, and 9% for the age at which first 10, 50, and 100 words were reported – in contrast to the value of 25% in the present study. It should be noted that heritability is based on the DIFFERENCE between two correlations. The correlation coefficient itself has large standard error, difficult to estimate from small samples (43 MZ pairs and 33 DZ pairs in Ganger *et al.*), and the difference between two such statistics is nearly twice as unreliable. Heritability estimates based on relatively small samples will have extremely wide confidence intervals, and in fact the confidence intervals estimated by Ganger *et al.* for each vocabulary measure include the 25% value estimated in the present study, based on a much larger sample. We suggest that latter value is likely to be more accurate, and in fact it is similar to other twin study estimates of the heritability of language measures in infancy. (The same argument applies to the estimates of shared environment influence.) An even more striking discrepancy occurred for the respective measures for the emergence of word combinations. Ganger *et al.* utilized a more focused and more stringent criterion. Parents were asked to record all the different phrases their children used each

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day. The researchers then counted a combination as productive only when all the words in it had appeared in previous combinations. With this definition, the estimated heritability for the emergence of word combinations was 90%, in contrast to the value of 39% in the present study. The issue of sample size is relevant here as for vocabulary; and again, the wide confidence interval estimated by Ganger *et al*. includes the value in the present study, 39%. However, it is also possible that the difference in the nature of the measures contributes to the difference in estimated heritabilities. Interestingly, a different measure of grammatical development – the appearance of over-regularized past tense forms – yielded a heritability of 44%, quite comparable to that of the grammar measure in the present study. Data collection is still in progress for Ganger *et al*., and the results may change with a larger sample.

Ganger *et al*. (1998) conclude from the low heritability of vocabulary and high heritability of grammatical development that the two are learned in different ways. As we note above, their results do not conclusively establish a difference in heritability between these two domains, given the small sample and wide confidence intervals. In addition, this question requires multivariate analyses rather than simply comparing univariate heritabilities. A substantial difference in heritabilities, if documented, would imply that genetic and environmental factors play a quantitatively different role in vocabulary and grammar, but whether or not they are the SAME factors can only be evaluated with a multivariate analysis.

As shown in Table 2, a strong phenotypic correlation of lexical and grammatical development consistent with previous results was observed here. The most important contribution of this study is the multivariate genetic analysis to determine the contribution of genetics and environment to this correlation. The analysis provided strong evidence for a genetic component. Genetic factors account for only 28% of the phenotypic covariance between these measures, but this statistic is limited by the fact that genes explain only a minority portion of variance in each. More revealing is the genetic correlation r_G of 0·61 between vocabulary and grammar, which establishes the substantial overlap in genetic factors which influence the two.

The present results fit well with those of a recent longitudinal study of Anisfeld, Rosenberg, Hoberman & Gasparini (1998). In their study of five children, the onset of combinatorial speech was found to coincide with an acceleration in lexical growth, rather than – as commonly assumed – following that lexical acceleration. Anisfeld *et al*. also noted a brief DECLINE in lexical growth following the emergence of combinations, which they attributed to a shift in attention from lexicon to grammar. The generality of this latter result bears further investigation, but it seems clear that large-sample studies such as the present one with relatively coarse time resolution and small-sample studies with finer time resolution have complementary

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strengths and can contribute to a more comprehensive account of development.

The phenotypic and genetic correlations between lexical and grammatical development found in the present study are compatible with a wide variety of explanations. Particularly tantalizing is the possibility of distinguishing the directionality of causation, that is, the relative influence of lexical bootstrapping and syntactic bootstrapping. Longitudinal analyses which use multivariate genetic analyses to decompose the 'cross-lagged' correlations $\text{vocabulary}_{t1} \Rightarrow \text{grammar}_{t2}$ and $\text{grammar}_{t1} \Rightarrow \text{vocabulary}_{t2}$ will provide valuable insight into this relation, and they are currently in progress.

Both phenotypically and with respect to behavioural genetic analysis, the links among these language measures show a coherence which does not extend to a measure of nonverbal development, the PARCA. The lower correlation with the PARCA is not a consequence of lower reliability for that measure; Saudino *et al.* (1998) found satisfactory internal consistency for the PARCA, comparable to language measures.

CONCLUSION

The domain specificity of cognition and cognitive development – modularity vs. molarity – is at the core of much current theorizing and controversy. The results of the present study, taken together with those of Price *et al.* (in press), suggest that – at age two, at least – it is a matter of resolution. At the highest, or 'coarsest' level, there is a clear distinction between verbal and nonverbal skills. But within the verbal domain, there is little evidence for strong distinctions or dissociations at this age, and specifically not for vocabulary and grammatical development. How this will play out over development is a fascinating question. It has been argued (Elman *et al.*, 1996) that a truly developmental theory will characterize domain specificity as an emergent property, not a wired-in structural property. We look forward to continuing behavioural genetic analyses of the development of children in this study.

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