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Genetic and environmental etiology of speech and word reading in Chinese
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Abstract

The present study examined the genetic and environmental etiology of the connection between speech and word reading in Chinese. A total of 371 pairs of Chinese twins (278 pairs of monozygotic twins and 93 pairs of same-sex dizygotic twins) were tested on speech discrimination and production, phonological skills, semantic skills, and Chinese word reading at the mean age 7.4 years. Results of univariate genetic analyses showed moderate genetic influences on speech, semantic skills, and Chinese word reading, while moderate shared environmental influences on phonological skills. The genetic correlations among all the variables were significant. Results of testing several models on the link between speech and word reading supported a common genetic factor underlying speech, phonological skills, semantic skills, and word reading in Chinese. The present findings suggest that around 50% to 60% of individual differences of speech, semantic skills, and word reading in Chinese are due to genetic factors. Individual differences of phonological skills appear to be relatively less heritable than those in English. This may be partly due to the fact that the Chinese script does not map directly on any segmental phonological information. A single common genetic etiology for speech, phonological skills, semantic skills, and word reading suggests that development of these skills is highly connected.

Keywords: Genetics; Speech; Word Reading; Chinese

1. Introduction

The close connection between speech and reading development has been well established in typically developing children and children with disorders. Many research findings have reported overlaps among speech sound disorder, language impairment, and reading disability in English (e.g., Pennington & Bishop, 2009; Peterson et al., 2007). Comorbidity among these disorders may suggest common underlying processes or common etiology. Deficits in the phonological pathway may be a common underlying cause for these speech-language related disorders in alphabetic languages. In some molecular genetic studies, genetic risk variants for speech sound disorder and reading disability were found to overlap (see review in Pennington & Bishop, 2009). Behavioral genetic studies with identical and fraternal twins learning to read English also show a significant genetic contribution of the early speech factor (based on articulation and nonword repetition) to later reading performance (Hayiou-Thomas et al., 2010). A strong genetic correlation between phonological awareness and word reading underscores the role of phonological skills in learning to read alphabetic languages (e.g., Gayan & Olson, 2001, 2003; Hayiou-Thomas et al. 2006). Most of these twin studies have been conducted in countries using alphabetic writing systems like US, UK, Australia, and Netherlands (see the meta-analysis of de Zeeuw et al. in 2015), very little is known about nonalphabetic writing systems. In nonalphabetic writing systems like Chinese, semantics, rather than phonological skills, may be more important for learning to read. The present study examines whether there is a close connection, both behaviorally and genetically, between speech and word reading development in Chinese. If yes, the study further examines whether the connection is through a phonological pathway, a semantic pathway, or both. We introduce our study by reviewing evidence for the speech-reading connection in some behavioral and genetic studies. Then we give an overview of the unique characteristics of the Chinese writing system and previous research on speech and reading in Chinese.

1.1 Continuities between the Development of Oral and Written Language

In learning an oral language, the first task of an infant is to master the perception and production of speech sounds. In the process of making sense of speech sounds, the child must determine which sound features are used to contrast different meanings and associated with which concepts. The speech sounds are thus represented phonologically and sequences of sounds are linked to semantic schemata in the mental lexicon. When a child's spoken vocabulary increases, phonological representation and its link to semantic representation may be refined (e.g., Metsala & Walley, 1998; Walley, Metsala & Garlock, 2003). It is clear that development of written language skills is built upon earlier oral language skills. In the triangle word reading model, learning words implies making associations among orthography, phonology, and semantics (Seidenberg & McClelland, 1989). Two key components of word reading development, namely phonology and semantics, overlap with those of speech development. Therefore, both phonological and semantic skills are in principle important for speech and word reading development. Although basic speech skills develop quite early and reading is typically acquired later, the developmental restructuring of phonological representation and continuous reorganization of the mental lexicon which occur between ages one and eight (Fowler, 1991) may link the development of speech and reading in some way.

1.2 Roles of Phonology and Semantics in the Development and Difficulties of Speech and Reading

It would be helpful to first distinguish between two terms, "speech" and "phonological awareness", as some people may find them confusing. Speech is the expression of or the ability to express thoughts and feelings by the articulation of words. Phonological awareness

refers to an individual's awareness of the phonological structure, or sound structure, of words which may involve detection and manipulation of sounds. Simple speech perceptual skills are believed to develop naturally when infants have enough exposure to a rich language environment. Children gradually develop some abstract mappings from listening and talking and these form a phonological representation of the speech event. Development of speech perception and production may also arouse a child's sensitivity to some phonological units like rhymes, and this phonological skill helps learning of written words, especially in alphabetic languages where orthographic units map onto sound units like phonemes. So speech may contribute to reading through its route in phonological skill development.

On the other hand, speech inputs also help a child to develop a system of lexical representation that facilitates the representation and extraction of word meaning. For instance, discrimination of two simple vowels measured by a conditioned head-turn task at 6 months predicted vocabulary size and other language scores at 13 to 24 months of age (Tsao, Liu, & Kuhl, 2004). Vocabulary knowledge further facilitates the creation of mappings among orthographic, phonological, and semantic representations in a child's developing lexicon. So speech may contribute to later reading indirectly through its influences on vocabulary and semantic development.

There has been far more empirical support for the connection between speech and reading via a phonological route than a semantic route from studies with disabled readers or typically-developing readers. For instance, after reviewing about 20 studies on speech perception, McBride-Chang (1995) concluded that individuals with reading disability are weak at processing speech, particularly stop consonants. Bird and colleagues (1995) also reported that children with speech difficulties at age 5 went on to have deficits on phonological awareness at ages 6 and 7, and the majority displayed literacy problems at age 7. Presence of additional language difficulties did not significantly affect children's literacy outcomes. It appears that the root cause for reading disability is a poorly specified phonological representation. Similar support was also found in typically-developing readers. Significant correlations were reported between speech perception, and phonological awareness, and between speech and reading (e.g., Carroll et al., 2003; Hurford, 1991; Roberts, 2005). Cheung (2007) has further reported that phonological awareness mediated significantly between speech processing and reading aloud. These findings suggest that the quality of phonological representation may be the underlying mechanism for the link between speech and reading development (e.g., Elbro, 1996). This may especially be the case in alphabetic languages.

1.3 Genetic Contributions to the Development and Difficulties of Speech and Reading

Given support from some behavioural studies for the close link between speech and reading development, we would like to know whether the link is also a genetic one. In a review of nearly a hundred genetic studies of normal variations in language skills, Stromswold (2001) have concluded that almost all aspects of language acquisition and linguistic proficiency, including articulation, phonology, vocabulary, morphosyntax, and orthographic decoding, are influenced by genetic factors to some extent.

In general, both speech and language skills are found to be heritable and speech skills (heritability ranged from 37% to 95%) are somewhat more heritable than language skills (heritability ranged from 29% to 87%) (e.g., DeThorne et al., 2006; Hayiou-Thomas et al., 2006a; Kovas et al., 2005). This may especially be the case for individuals with specific language impairment (SLI). Bishop and Hayiou-Thomas (2008) reported that "Clinical SLI" was highly heritable (97%) while "Psychometric SLI" was entirely environmental. It was interesting that the "Clinical SLI" group had much lower speech scores than the "Psychometric SLI" group. It appears that speech deficits are the locus of genetic effects on

language impairments and the speech deficits were more heritable than broader language deficits.

Given the high heritability of speech and language skills, how do the two skills relate to reading in both behavioural and genetic terms? In a UK longitudinal twin study, Hayiou-Thomas et al. (2010) reported that preschool speech and language skills were predictive of reading throughout the elementary school years. Both genetic and environmental factors played a role in the relationship between oral language skills and subsequent reading, but genetic factors played a much stronger role in the relationship between speech skills and later reading. However, it is noteworthy that nonword repetition, a measure of phonological short-term memory, was included in the speech factor of this study. This might have elevated the connection between speech and reading in the study.

Apart from speech and language skills, phonological skills have also been found in many behavioural studies to be salient for learning to read alphabetic orthographies. Would this relationship have any genetic foundation? Phonological awareness and phonological memory have been found to have moderate to strong heritability (ranged from 38% to 83%) (e.g., Bishop et al., 1999; Gayan & Olson, 2003; Kovas et al., 2005). The genetic correlation between the two phonological skills and reading was found to be moderate to strong (Gayan & Olson, 2003; Hayiou-Thomas et al., 2006b). This suggests that phonological skills and reading may share some common genetic factors.

As for semantic skills, vocabulary is considered as a measure of individual differences in how well semantic and lexical knowledge is acquired. Unlike speech and phonological skills, the heritability of vocabulary is somewhat lower with a group heritability of 33% in Stromswold's (2001) meta-analysis of eight studies. However, Olson and his colleagues showed that the genetic contribution to vocabulary increased with age, from .29 in pre-kindergarten to .44 in Grade 2, to .57 in Grade 4 (Olson et al., 2011). The strong genetic role of the speech-reading link in alphabetic languages reviewed above raises the question of whether such a link would be found in a nonalphabetic script, Chinese. Although the genetic role of semantic skills has been relatively less examined, it may be important for learning to read Chinese, a morphosyllabic writing system. Characteristics of the Chinese language will be reviewed briefly below.

1.4 Characteristics of the Chinese Writing System

The basic graphic unit in Chinese is a character. The fact that the Chinese character is simultaneously a visual whole, a syllabic unit, and a morpheme contrasts with the orthographic unit in alphabetic scripts, letter, which indicates sound only. The Chinese script may be directly interpreted for meaning without obligatory phonemic processing, because phonemic segments are not coded directly in Chinese writing (e.g., Ho & Bryant, 1997a). There are a lot of homophones and compound morphology in Chinese. Discrimination of morphemic meaning has been found to be important for learning to read Chinese and morphological awareness also correlate highly with vocabulary in Chinese (e.g., McBride-Chang et al., 2003, 2005; Shu et al., 2006). As such, the semantic or meaning pathway may be more important than the phonological pathway in reading Chinese. One obvious advantage of this logographic and morphosyllabic nature of the Chinese language is that the same script can be used in a large population where people speak different dialects.

1.5 Chinese Twin Study of Reading Development

The Chinese Twin Study (CTS) of reading development was the first to investigate genetic and environmental influences on Chinese language and reading abilities and to examine whether the roles of heredity and environment would be similar to those in alphabetic languages. Findings of this study have been reported in several papers (e.g., Chow

et al., 2011, 2013; Ho et al., 2012). For instance, Chow and her colleagues (2011) reported that the genetic contributions to word reading, phonological memory and rapid naming, and the shared environmental influences on receptive vocabulary are likely to be universal across languages; whereas the importance of shared environment on rhyme and syllable awareness seems to be unique to Chinese (Shu, McBride-Chang, Wu, & Liu, 2006). The present study was part of the CTS.

1.6 Research Findings Related to Speech and Reading in Chinese

Before approaching the question in genetic terms, we first considered whether there is a significant behavioural link between speech and reading development in Chinese, and whether phonological and semantic skills play a role in the relationship. Some behavioural studies indicated a close connection between speech and reading in Chinese. For instance, Cheung and his colleagues found that speech perception significantly predicted phonological awareness, vocabulary, and reading in Chinese children after controlling for metalinguistic awareness (Cheung et al., 2010). Similarly, Liu and colleagues (2010) also reported that articulation at age 3, and sentence imitation at age 4 significantly distinguished poor from adequate Chinese readers at age 7. It appears that there is also a close connection between speech and reading development in Chinese.

The next question is whether the relationship is mediated by a phonological or a semantic pathway. Many studies have shown that phonological skills play a limited role in learning to read Chinese. Earlier studies have shown that phonological awareness and phonological memory are significant correlates of beginning word reading in Chinese (Ho & Bryant, 1997b; Hu & Catts, 1998). However, more recent studies have reported that when other reading-related skills (e.g., orthographic skills and morphological awareness) were controlled, phonological awareness no longer predicted Chinese word reading either concurrently or longitudinally (Yeung et al., 2011). Given the dominance of compound morphology in Chinese, understanding the meaning of morphemes and their compounding rules is important for word learning in Chinese. Hence, the role of morphological awareness may reflect how children get at the meaning of words, i.e., an indicator of the semantic pathway of word learning. Past studies have demonstrated that morphological awareness plays a much more significant role in Chinese word reading than that of phonological skills. For instance, morphological awareness predicted word reading and reading comprehension in Chinese over and above phonological skills (McBride-Chang et al., 2003, 2005; Shu et al., 2006). Morphological awareness also distinguished Chinese dyslexic children from average readers among Grade 5 and Grade 6 children in Beijing, and Chinese kindergarten children at risk or not at risk for dyslexia in Hong Kong (McBride-Chang et al. 2008; Shu et al., 2006). These findings suggest that the semantic pathway may be more important than the phonological pathway in reading Chinese.

1.7 Aims of the Present Study

From the review above, we learn that speech is highly heritable, and it is strongly related to phonology and reading in English but the role of semantics is relatively less examined. Chinese would be a good test case to examine the universality of the roles of phonology and semantics in speech and reading development. Given the characteristics of Chinese, we expect that semantics and word morphology may play a more important role than phonology for the link between speech and reading in Chinese. The present study aimed at (1) investigating the relative genetic and environmental influences on the various language-related abilities, including speech, phonology, semantics, and word reading in Chinese, and (2) comparing the goodness of fit of four proposed models with different involvement of the phonological pathway or semantic pathway (details will be described

below) and to see which model could best explain the possible etiology of the connection between speech and word reading in Chinese. In the present study, speech was measured by a speech perception task and a speech production task (e.g., Cheung et al., 2010, Liu et al., 2010). Phonological skills were measured by a phonological awareness task and a phonological memory task (e.g., Ho et al., 2004), while semantic skills were measured by a receptive vocabulary task and a morphological awareness task (e.g., Shu et al., 2006). These were common measures of the respective constructs employed in past studies.

For the first research question, we would like to examine the proportion of genetic and environmental influences on each of the four language-related skills individually using univariate genetic analysis. Univariate genetic models (e.g., ACE models) can decompose the observed variance in a single phenotype (e.g., speech or word reading) into proportions due to additive effects of multiple genetic loci (A), to shared environmental effects (C), and to unique environmental effects (E), which make twins differ. We wonder whether some of the language-related skills, like speech, are more heritable than others. We also examined how the four skills may share genetic and/or environmental influences using multivariate genetic analysis with Cholesky decomposition. Some of the skills, like speech and phonological skills, may share stronger genetic origin than other skills.

Regarding the second research question, we aimed at understanding how genetic factors may contribute to the close connection between speech and word reading. We tested four models on the relationship among the examined language-related skills (see Figure 1). In Model 1, we hypothesize a single common genetic factor underlying speech, phonological skills, semantic skills, and word reading. This proposes that the reason for the close association among these constructs is that they are all affected by the same set of genes. Model 2 proposes that the link between speech and reading is mainly mediated by a common phonological pathway. In other words, there are two separate sets of genes affecting speech and word reading but they share the same genetic influences on phonological skills and this contributes indirectly to the association between speech and reading. A similar logic applies to Model 3 with the only change from the phonological pathway to the semantic pathway as the mediator between speech and reading. This model suggests that speech and word reading in Chinese may be associated genetically because the different genes on speech and word reading both contribute to the development of semantic skills. Model 4 also suggests two separate sets of genes for speech and reading but they share the genetic influences on both phonological and semantic skills. In other words, both phonological and semantic skills mediate the link between speech and word reading. Results of these model comparisons would suggest whether same or different sets of genes may contribute to the development of speech and word reading skills and the pathways for the connected genes. Multivariate genetic models additionally examine the cross-correlations between twins for different traits together to allow us to determine the extent to which genetic influences are shared in common by several traits (e.g., whether speech and word reading share common source of genetic influences).

2. Materials and Methods

2.1 Ethics statement

Ethical approval was obtained from the Human Research Ethics Committee for Non-clinical Faculties of the University of Hong Kong. Parental written consent was also sought from each participant.

2.2 Participants & Procedures

The present paper reports data from the Chinese Twin Study (CTS) of reading development. The CTS included a sample of around 400 pairs of unselected monozygotic

(MZ) and same-sex dizygotic (DZ) twins from Hong Kong, China. As in some behavioural genetic studies, DZ opposite sex twins were not included because boys and girls might perform differently in speech and reading (e.g., Olson et al., 2011). All the kindergartens and elementary schools in Hong Kong were invited to participate. As we have reported in our other papers (e.g., Chow et al., 2011, 2013; Ho et al., 2012), the same-sex DZ to MZ twin ratio was 0.35 in the whole CTS sample. In general, the DZ and MZ twinning ratio tends to be lower in Asian populations (Imaizumi, 2003). The proportion of twin types in the CTS sample was comparable to that of the population prevalence. Children in the CTS sample had been tested once annually for three years on a broad range of speech, language, cognitive, and literacy skills.

In the present study, we report the results of the CTS measures of speech, phonological skills, semantic skills, and word reading administered in Wave 2 of the study. In general, children in Hong Kong enter kindergarten and primary school at around age 3 and age 6 respectively, and are provided with 3 years of kindergarten education and 6 years of primary education. Children in Hong Kong are typically introduced to reading and writing of Chinese at age 3 or 4 years. The Wave 2 sample consisted of 278 pairs of MZ twins (141 male pairs and 137 female pairs) and 93 pairs of DZ twins (56 male pairs and 37 female pairs) aged from 4 to 12 years with a mean age of 7.42 years and a SD of 1.96 years when they were assessed on these measures. The children were mostly tested at their home, sometimes at their school or our laboratory. Although there was a variation in testing environments, the experimenters ensured that the testing rooms were quiet and the children were tested alone without the presence of other adults like their parents or teachers. Chinese was the first language for all the participants. SNP testing was conducted to determine twin pairs' zygosity.

2.3 Measures

The measures included in the present study were from the larger test batteries that were administered in the CTS.

2.3.1 Speech

2.3.1.1 *Speech perception.* This was a test of AXB speech perception of phonemic contrasts and it was adapted from Bishop's owl test (Bishop, Adams, Nation, & Rosen, 2005). The children were asked to choose from two Chinese syllables which sounded the same as the target one in the context of a computer game. Results from the pilot testing indicated that the test was too easy for older participants, so we combined speech-like noise and the Chinese syllables with a signal-to-noise ratio of -12dB. In each item, a correct response was rewarded with a cartoon picture appearing on the computer screen, while an incorrect one was given a 'sigh' sound. There were 6 practice and 24 test items. The Kuder-Richardson 20 (KR20) of this task was .82.

2.3.1.2 *Speech production.* Part I of the Cantonese Segmental Phonology Test (So, 1993) was used to test the children's Cantonese articulation accuracy. It was a standardized test of children's contrastive use of phonemes in their phonetic inventory, and hence a measure of their speech production in Cantonese. The test contained 31 one- or two-syllable items, each with a color photograph of a common object. There were altogether 38 syllables which covered all the Cantonese phonemes and tones. The children were asked to name the photographs one by one. If a child was not able to produce the name of the photograph, he/she would be prompted by questions or asked to imitate the name said by the experimenter. Each correctly pronounced syllable carried one mark. The Cronbach's alpha was .85.

2.3.2 Phonological Skills

2.3.2.1 *Phonological awareness.* Phonological awareness in this study was measured by syllable deletion and rhyme detection. In the syllable deletion part, there were 15 items each with two- or three-syllable word or nonword. The child was asked to delete a syllable from

the given word or nonword. The rime detection part consisted of 9 test items. In each item, the experimenter read out a target syllable, and then read out three syllables each of which was illustrated by a picture. The child was required to select a syllable from the three options which rhymed with the target syllable. The maximum score of the combined task was 24, and its Cronbach's alpha was .85.

2.3.2.2 Phonological memory. A nonword repetition task was used to assess children's phonological memory in this study. There were 14 items of nonword strings each ranged from two syllables to seven syllables. A nonword string was a combination of Cantonese syllables which had no lexical meaning as a whole (e.g., /ga1 kwan1/). The child was asked to repeat orally each nonword string immediately after being presented by the experimenter. One point was given for each correctly repeated syllable and another point for each correct order of consecutive syllable pair. The testing was discontinued when the child failed four consecutive items. The maximum score was 124, and its Cronbach's alpha was .89.

2.3.3 Semantic Skills

2.3.3.1 Receptive vocabulary. Receptive vocabulary was measured with a translated and adapted version of the Peabody Picture Vocabulary Test – Fourth Edition (PPVT-IV) (Dunn & Dunn, 2007). There were 2 practice and 80 test items. For each item, the experimenter read out the target vocabulary and the child was required to select a picture from the four options to match it. The items were ranked in increasing order of difficulty. Correct responses given in 9 or all items in the first 10 consecutive items fulfilled the basal rule. Testing stopped when the child failed to identify 15 consecutive items. The maximum score of this test was 80 and the Cronbach's alpha was .95.

2.3.3.2 Morphological awareness. In order to have a comprehensive measure of morphological awareness and to have a wide range of difficulties suitable for preschool as well as school age children, there were three subtasks which were arranged in an order of increasing difficulty. Testing was discontinued when the child failed 4 out of 5 consecutive items. *The receptive morphological awareness subtask* had 10 items. For each item, a novel concept created by a combination of morphemes was orally presented to the child. The child was then required to select a picture from the five options which illustrated the target item. For example, the novel concept was a striped elephant (斑象 /baan1 zoeng6/) and the five picture options were (a) a zebra (斑馬/baan1 maa5/), (b) a striped dog (斑狗 /baan1 gau2/), (c) stripes and an elephant (斑+象/baan1/ + /zoeng6/), (d) a dog and an elephant (狗+象 /gau2/ + /zoeng6/), and (e) a striped elephant (斑象 /baan1 zoeng6/). *The morphological construction subtask* had 12 items. For each item, a scenario was orally presented by the experimenter, and the child was asked to construct words for the novel objects or concepts according to the scenarios. For instance, “An island that is full of yellow chrysanthemums, is called a yellow chrysanthemum island (黃菊島 /wong4 guk1 dou2/). What will we call the island which is full of red peach?” The expected answer was a red peach island (紅桃島 /hung4 tou4 dou2/). A correct answer was awarded two points, and a partially correct answer was awarded one point. *The homophone subtask* consisted of 5 items. For each item, a single-syllable character was orally presented in the context of a word, and the child was asked to produce in 10 seconds words with the target character and had similar meaning. The child was then asked to produce in 10 seconds other words with a character homophonic with the target one. For example, the target character is ‘兒’ of the word ‘兒童’ (children /ji4 tung4/). The words constituting this character with similar meaning can be ‘兒子’ (son /ji4

zi2/), while the words composed of its homophones can be ‘懷疑’ (suspect /waa14 ji4/). The total score of the combined task was 44, and its Cronbach’s alpha was .94.

2.3.4 Word Reading

The word reading test consisted of a 48-item character reading list and 150 items adapted from the Chinese Word Reading subtest of the Hong Kong Test of Specific Learning Difficulties in Reading and Writing (HKT-SpLD) (Ho, Chan, Tsang, & Lee, 2000). The HKT-SpLD is a standardized test developed for Hong Kong primary school children, and items in the Chinese Word Reading subtest are common Chinese two-character words of Grade 1 to Grade 6 levels. The words were arranged in an order of increasing difficulty. The child was required to read each word aloud. Testing was discontinued when the child failed to read 15 consecutive items. The maximum score was 198 and the Cronbach’s alpha was .995.

2.4 Procedure

Each child was tested individually for around one hour each time on a battery of tests by trained research assistants, psychology major undergraduates or graduates in the child’s school, home, or our laboratory in Hong Kong according to the parents’ preference. Saliva was collected from co-twins with DNA kits for zygosity assessment.

3. Results

3.1 Phenotypic Analyses

Table 1 shows the mean raw scores and standard deviations of the measures by sex and zygosity, and the intra-class twin correlations. All correlations among the MZ twins were greater than those among the DZ twins. We used Principal Component Analysis (PCA) to confirm the three cognitive-linguistic components in the present study. The component of speech being measured by speech perception (with loading of .85) and speech production (with loading of .85) explained 72.9% of total variance. The component of semantic skills being measured by vocabulary (with loading of .94) and morphological awareness (with loading of .94) explained 93% of total variance. The component of phonological skills being measured by phonological awareness (with loading of .89) and phonological memory (with loading of .89) explained 79.9% of total variance. The PCA scores were used as dependent variables in later genetic analyses.

3.2 Genetic Analyses

To address the research questions in the present study, univariate and multivariate genetic analyses were conducted with OpenMx in the R statistical modeling package (Boker, Neale, Maes, Wilde, Spiegel, Brick, et al, 2011). We first tested the assumptions of equal means and equal variances of the task performance across MZ and DZ twins by progressively constraining the saturated model in each task (step 1: fixing expected means to be equal across twin order, step 2: fixing expected means and variances to be equal across twin order, and step 3: fixing expected means and variances to be equal across twin order and zygosity). Model comparisons against the saturated model indicated that none of the constrained models was significantly better than the saturated model (all $\Delta\chi^2 < 8.92$, all $ps > .08$). This suggests that our data meet the assumption of equal means and variances across MZ and DZ twins for genetic analyses.

Although that was not the main focus of the present paper, we also looked at the potential age effect and gender effect in the univariate genetic analyses using age and gender as moderators (Purcell, 2002). Table 2 shows that dropping age, but not gender, would significantly deteriorate the model index for all the skill domains except speech. In other words, the pattern of genetic and environmental contributions to each examined skill was mainly influenced by different ages but speech was influenced by both age and gender. For simplicity, we only controlled for age in subsequent multivariate genetic analyses. Next we also looked at whether the influence of age to each skill domain was linear or quadratic.

Table 3 shows the proportions of variance in each skill domain due to genetic (a^2), shared environmental (c^2), and unique environmental effects (e^2) for both results using age as a linear regressor and using the standardized residuals of quadratic regression models. It was found that a quadratic function fitted all of the skill domains better than a linear function did (all quadratic models had lower AIC than linear models and all the quadratic terms were significant with $p < .001$). So age was controlled using quadratic regression models in later multivariate genetic analyses.

Overall, Table 3 shows that speech, semantic skills, and word reading had moderate to strong heritability (a^2 ranged from .51 to .62) while environmental influences common to both twins exerted a stronger effect than genetic ones on phonological skills ($c^2 = .40$). As mentioned above, gender was a significant moderator that influenced the genetic and environmental contribution to speech. It was found that heritability of speech was stronger for girls ($a^2 = .53$) than for boys ($a^2 = .04$) while boys ($c^2 = .63$) were more affected by environmental factors than girls ($c^2 = .00$).

Multivariate genetic analyses using the Cholesky decomposition model (Neale, Boker, Xi, & Maes, 2006) were also conducted to investigate the genetic and environmental links among speech, phonological skills, semantic skills, and word reading in Chinese. Cholesky decomposition breaks down phenotypic covariances among variables into their shared and independent variance associated with genes, shared environment, and unique environment. The order of the variables in the Cholesky analysis was determined according to some conceptual priority. The order from speech, phonological skills, semantic skills, and word reading roughly follows the order of acquisition in children. See Figure 2 for the illustration of various paths of the genetic component of the Cholesky model. The paths are the same for the shared and unique environment components. Table 4 presents the Cholesky results of the genetic (A), shared environmental (C), and unique environmental (E) standardized path estimates of the four skill domains. It was found that speech (A1) shared significant genetic influence with phonological skills (.46), semantic skills (.63), and word reading (.42). Phonological skills or semantic skills did not share significant genetic influence with word reading when the genetic influences on either speech (A2) or both speech and phonological skills (A3) were controlled.

In general, the environmental influences common to both twins were much weaker than those of the genetic ones. Like the results of univariate genetic analyses, only phonological skills (C2) had significant shared environmental effect (.53). As for the unique environmental influences, all of the large significant effects were on the diagonal ($E1 = .60$ for speech, $E2 = .51$ for phonological skills, $E3 = .49$ for semantic skills, and $E4 = .30$ for word reading), which indicated some unique environmental factors specific to speech, phonological skills, semantic skills, and word reading respectively, and these unique environmental effects were not shared with other factors. We suspect that this might be partly a result of test measurement error.

In order to test which model best depicts the relationship between speech and reading, the goodness of fit of the four proposed models was compared with the Cholesky model as the baseline of which no a priori assumption was made on the communality of genetic factors. Table 5 shows the fit statistics of the various models in the whole sample. It was found that Model 1, with a single common genetic factor, was the best model with the least number of estimated parameters and non-significant deterioration in fit as compared with the baseline model ($\Delta X^2 = 3.14$, $p = .792$). We then tried to see whether we could further simplify the model by dropping the C paths. However, dropping the C paths resulted in a significant deterioration in fit ($\Delta X^2 = 36.24$, $p < .001$). Therefore, the full ACE Model 1 seems to be the best model for describing the relationship between speech and word reading. Figure 3 shows the path estimates of Model 1. It appears that the common genetic factor loads relatively

stronger on speech, phonological skills, and semantic skills than word reading.

Table 6 shows the genetic and environmental correlations among the four skill domains, with genetic correlations presented above the diagonal and shared environmental correlations below the diagonal. Strong genetic correlations were observed among speech, phonological skills and semantic skills (all $r_s > .77$). On the other hand, all the shared environmental correlations were not significant.

4. Discussion

To recap, the primary aim of the present study was to examine the etiology of the connection between speech and word reading in Chinese. To the best of our knowledge, this is the first study examining the genetic etiology of the connection between speech and word reading in a nonalphabetic script. It was found that around 50 to 60 percent of individual differences of speech, semantic skills, and word reading in Chinese was due to genetic factors, while phonological skills were relatively more affected by shared environmental factors.

Although we did not set out to examine the gender effect but there were some interesting findings regarding the different patterns of genetic contributions between male and female groups. Gender appears to influence the genetic and environmental contributions to speech development. It was found that there were greater genetic influences in the female group than in the male group for speech (53% vs. 4%). There has been a long history on the study of speech/language and gender (e.g., the review by Speer, 2005) and we are not going into the details here. Girls have traditionally been found to have better speech and language performance than boys. We might be led to think that this is mainly genetic. However, the present findings show that the cause of individual differences in speech is more genetic for girls but environmental for boys. If this is established, that means factors like home and school language environment may be important in affecting the speech and language development of boys. We are not aware of any past genetic studies reporting similar gender differences in the pattern of genetic and environmental contribution to language-related skills. The present findings may have potential implications for educating boys and girls differently and future validation with larger sample sizes is required.

The present findings with relatively more environmental influences on phonological skills seems to be special in Chinese as the genetic influences of phonological skills in English have generally been found to be greater. This may be due to the characteristics of the Chinese script. There is no segmental phonological information in Chinese characters and special training may be required for Chinese children to be sensitive to phonological information, and thus environment plays an important role. Children's sensitivity to phonology may be affected by their exposure to learning English as a second language. However, there are great variations of how English is taught in Hong Kong schools. Fujisawa and her colleagues (2013) also found that shared environmental influences play an important role in phonological skills and prereading skills among three-year-old Japanese twins. Sensitivity to mora is required for learning Japanese Kana though not necessarily sensitivity to phonemes as in the case of learning alphabetic languages. It appears that the little genetic contribution to phonological skills and prereading skills in Fujisawa et al.'s study is mainly due to great environmental variations in learning among the younger children. Further findings regarding the etiology of the connection between speech and word reading in Chinese will be elaborated below.

4.1 The Link between Speech and Word Reading

The first question we would like to address is the nature of speech, and the speech-reading link in Chinese. Results of the multivariate genetic analyses show that when the genetic influence of speech was controlled, there was no significant genetic influence left

for phonological skills (a22 in Figure 2 and Table 4) but that for semantic skills was still significant after controlling speech and phonological skills (a33 in Figure 2 and Table 4). This suggests that speech discrimination and articulation is highly phonological in nature. This is consistent with past findings that speech perception was significantly correlated with phonological awareness (e.g., Carroll et al., 2003; Hurford, 1991; Roberts, 2005), and early speech difficulties are related to later phonological deficits (e.g., Bird et al., 1995). This might also partly relate to how speech was measured in the present study. Since both speech perception and production tasks mainly involved speech sound discrimination and articulation, not much semantic understanding was required.

In the same multivariate genetic analyses, after controlling for the genetic influences of both speech and phonological skills, semantic skills no longer shared significant genetic influence with that of Chinese word reading (a43 in Figure 2 and Table 4). This may suggest that the genetic linkage between speech and Chinese word reading is both phonological and semantic in nature. This is contrary to our expectation that semantics may play a more important role than phonology in the genetic link. Although semantic skills may be more important than phonological ones in reading Chinese words, both skills are believed to be essential for listening and reading. Therefore the continuities between speech and reading development are likely through the overlapping roles of phonological and semantic skills.

Results of the correlation analyses are consistent with the above findings. There are strong and significant genetic correlations among all the linguistic skills, especially those among speech, phonological skills, and semantic skills ($r_g = .78$ to $.83$). This may suggest that these linguistic skills are influenced by common genetic factors.

4.2 Separate or Common Etiology for the Connection between Speech and Word Reading

Since the above findings show that the connection between speech and word reading involves both phonological and semantic skills, Model 2 (phonological pathway mediation) and Model 3 (semantic pathway mediation) may not reflect the relationship between speech and word reading. Results of the model testing show that Model 1 (single common genetic factor) fits the data better than the other three models. Therefore, our findings support a single common genetic etiology for speech, phonological skills, semantic skills, and word reading in Chinese rather than two separate genetic factors for speech and reading. This implies that children, who are good in speech development, may tend to also develop better phonological and semantic skills, and in turn better reading skills. Understanding and production of speech sounds help the abstraction and mental representation of the phonological elements and the building up of mental lexicons. In other words, spoken and written language development may have the same genetic origin. This may support the idea of some general language skills which are fundamental to both spoken and written language development. Although this study was not examining children with disorders, the present findings may provide indirect support for the possible common genetic etiology for Speech Sound Disorder, language impairment, reading disorder, and phonological difficulties.

4.3 Limitations

The major limitation of the present study was that the present sample size was relatively small and there was a wide age range for the participants. A larger sample with a smaller age range is desirable for examination of specific developmental patterns longitudinally. In addition, the unbalanced MZ and DZ sample might not be ideal as it would somehow decrease the power to detect shared environmental effect. Although this is a typical characteristic among Asian twin populations, similar future studies may consider including opposite-sex twins to increase the power to detect shared environmental effect.

4.4 Conclusions and Future Directions

The present study examined the etiology of the connection between speech and word reading in Chinese. It was found that individual differences of speech, semantic skills, and word reading in Chinese are highly heritable. The genetic linkage between speech and Chinese word reading is both phonological and semantic in nature. A single common genetic etiology for speech, phonological skills, semantic skills, and word reading suggests that those who are good in speech, may also develop better phonological and semantic skills, and in turn facilitates later development of reading skills. In the multivariate genetic analyses, there are around 37 percent of genetic influence on Chinese word reading not accounted for by speech, phonological, and semantic skills, the role of other word reading related skills like orthographic processing skills may be examined in future studies. In general, development of semantic skills has been neglected in genetic research of reading and should be better examined in the future.

References

- Aaron, P. G., Joshi, M., & Williams, K. A. (1999). Not All Reading Disabilities Are Alike. *Journal of Learning Disabilities*, 32(2), 120-137. doi:10.1177/002221949903200203
- Betjemann, R. S. (2009). Assessment and etiology of individual differences in reading comprehension. *Beyond decoding: The behavioral and biological foundations of reading comprehension*, 227.
- Betjemann, R. S., Keenan, J. M., Olson, R. K., & DeFries, J. C. (2011). Choice of reading comprehension test influences the outcomes of genetic analyses. *Scientific Studies of Reading*, 15(4), 363-382.
- Bird, J., Bishop, D., & Freeman, N. (1995). Phonological awareness and literacy development in children with expressive phonological impairments. *Journal of Speech, Language, and Hearing Research*, 38(2), 446-462.
- Bishop, D., Adams, C., Nation, K., & Rosen, S. (2005). Perception of transient nonspeech stimuli is normal in specific language impairment: Evidence from glide discrimination. *Applied Psycholinguistics*, 26(02), 175-194.
- Bishop, D., & Hayiou-Thomas, M. (2008). Heritability of specific language impairment depends on diagnostic criteria. *Genes, Brain and Behavior*, 7(3), 365-372.
- Bishop, D. V., Bishop, S. J., Bright, P., James, C., Delaney, T., & Tallal, P. (1999). Different Origin of Auditory and Phonological Processing Problems in Children With Language Impairment Evidence From a Twin Study. *Journal of Speech, Language, and Hearing Research*, 42(1), 155-168.
- Boker, S., Neale, M., Maes, H., Wilde, M., Spiegel, M., Brick, T., . . . Bates, T. (2011). OpenMx: an open source extended structural equation modeling framework. *Psychometrika*, 76(2), 306-317.
- Byrne, B., Coventry, W. L., Olson, R. K., Samuelsson, S., Corley, R., Willcutt, E. G., . . . DeFries, J. C. (2009). Genetic and environmental influences on aspects of literacy and language in early childhood: Continuity and change from preschool to Grade 2. *Journal of Neurolinguistics*, 22(3), 219-236.
- Byrne, B., Samuelsson, S., Wadsworth, S., Hulslander, J., Corley, R., DeFries, J. C., . . . Olson, R. K. (2007). Longitudinal twin study of early literacy development: Preschool through Grade 1. *Reading and Writing*, 20(1-2), 77-102.
- Carroll, J. M., Snowling, M. J., Stevenson, J., & Hulme, C. (2003). The development of phonological awareness in preschool children. *Developmental psychology*, 39(5), 913.
- Catts, H. W., Hogan, T. P., & Adlof, S. M. (2005). Developmental changes in reading and reading disabilities. In H. W. C. A. G. Kamhi (Ed.), *The connections between language and reading disabilities* (pp. 25-40). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.
- Catts, H. W., Hogan, T. P., & Fey, M. E. (2003). Subgrouping poor readers on the basis of individual differences in reading-related abilities. *Journal of Learning Disabilities*, 36(2), 151-164.
- Cheung, H. (2007). The role of phonological awareness in mediating between reading and listening to speech. *Language and Cognitive Processes*, 22(1), 130-154.
- Cheung, H., Chung, K. K. H., Wong, S. W. L., McBride-Chang, C., Penney, T. B., & Ho, C. S.-H. (2010). Speech perception, metalinguistic awareness, reading, and vocabulary in Chinese-English bilingual children. *Journal of Educational Psychology*, 102(2), 367.
- Chia, K., Lee, J., Cheung, P., Cheung, K., Seielstad, M., Wilcox, M., & Liu, E. (2004). Twin births in Singapore: A population-based study using the national birth registry. *ANNALS-ACADEMY OF MEDICINE SINGAPORE*, 33(2), 195-199.
- Chik, P. P.-m., Ho, C. S.-h., Yeung, P.-s., Wong, Y.-k., Chan, D. W.-o., Chung, K. K.-h., & Lo, L.-y. (2012). Contribution of discourse and morphosyntax skills to reading

- comprehension in Chinese dyslexic and typically developing children. *Annals of dyslexia*, 62(1), 1-18.
- Chow, B. W.-Y., Ho, C. S.-H., Wong, S. W.-L., Waye, M. M. Y., & Bishop, D. V. M. (2013). Generalist Genes and Cognitive Abilities in Chinese Twins. *Developmental Science*, 16, 260-268.
- Chow, B. W.-Y., Ho, C. S.-H., Wong, S. W.-L., Waye, M. M., & Bishop, D. V. (2011). Genetic and environmental influences on Chinese language and reading abilities. *PloS one*, 6(2), e16640.
- Curtis, M. E. (1980). Development of components of reading skill. *Journal of Educational Psychology*, 72(5), 656.
- DeThorne, L. S., Hart, S. A., Petrill, S. A., Deater-Deckard, K., Thompson, L. A., Schatschneider, C., & Davison, M. D. (2006). Children's history of speech-language difficulties: Genetic influences and associations with reading-related measures. *Journal of Speech, Language, and Hearing Research*, 49(6), 1280-1293.
- De Zeeuw, E. L., de Geus, E. J. C., Boomsma, D. I. (2015). Meta-analysis of twin studies highlights the importance of genetic variation in primary school educational achievement. *Trends in Neuroscience and Education*, 4, 69-76.
- Dunn, L. M., & Dunn, D. (2012). Peabody Picture Vocabulary Test, (PPVT™-4). *Johannesburg: Pearson Education Inc.*
- Elbro, C. (1996). Early linguistic abilities and reading development: A review and a hypothesis. *Reading and Writing*, 8, 453-485.
- Fowler, A. E. (1991). How early phonological development might set the stage for phoneme awareness. *Phonological processes in literacy: A tribute to Isabelle Y. Liberman*, 97, 117.
- Fujisawa, K. K., Wadsworth, S. J., Kakhana S., Olson, R. K., DeFries, J. C., Byrne, B., & Ando, J. (2013). A multivariate twin study of early literacy in Japanese Kana. *Learning and Individual Differences*, 24, 160-167.
- Gayán, J., & Olson, R. K. (2001). Genetic and environmental influences on orthographic and phonological skills in children with reading disabilities. *Developmental Neuropsychology*, 20(2), 483-507.
- Gayán, J., & Olson, R. K. (2003). Genetic and environmental influences on individual differences in printed word recognition. *Journal of Experimental Child Psychology*, 84(2), 97-123.
- Gough, P. B., & Tunmer, W. E. (1986). Decoding, Reading, and Reading Disability. *Remedial and Special Education*, 7(1), 6-10.
- Harlaar, N., Cutting, L., Deater-Deckard, K., DeThorne, L. S., Justice, L. M., Schatschneider, C., . . . Petrill, S. A. (2010). Predicting individual differences in reading comprehension: A twin study. *Annals of dyslexia*, 60(2), 265-288.
- Harlaar, N., Hayiou-Thomas, M. E., Dale, P. S., & Plomin, R. (2008). Why do preschool language abilities correlate with later reading? A twin study. *Journal of Speech, Language, and Hearing Research*, 51(3), 688-705.
- Hayiou-Thomas, M. E., Harlaar, N., Dale, P. S., & Plomin, R. (2010). Preschool speech, language skills, and reading at 7, 9, and 10 years: Etiology of the relationship. *Journal of Speech, Language, and Hearing Research*, 53(2), 311-332.
- Hayiou-Thomas, M. E., Harlaar, N., Dale, P. S., & Plomin, R. (2006). Genetic and environmental mediation of the prediction from preschool language and nonverbal ability to 7-year reading. *Journal of Research in Reading*, 29(1), 50-74.
- Hayiou-Thomas, M. E., Kovas, Y., Harlaar, N., Plomin, R., Bishop, D. V., & Dale, P. S. (2006). Common aetiology for diverse language skills in 4½-year-old twins. *Journal of child language*, 33(2), 339.

- Ho, C. S.-H., & Bryant, P. (1997a). Learning to read Chinese beyond the logographic phase. *Reading Research Quarterly*, 32, 276-289.
- Ho, C. S.-H., & Bryant, P. (1997b). Phonological skills are important in learning to read Chinese. *Developmental psychology*, 33(6), 946.
- Ho, C. S.-H., Chan, D., Tsang, S., & Lee, S. (2000). The Hong Kong test of specific learning difficulties in reading and writing. *Hong Kong: Hong Kong Specific Learning Difficulties Research Team*.
- Ho, C. S.-H., Chan, D., Lee, S., Tsang, S., & Luan, V. H. (2004). Cognitive profiling and preliminary subtyping in Chinese developmental dyslexia. *Cognition*, 91, 43-75.
- Ho, C. S.-H., Chow, B. W.-Y., Wong, S. W.-L., Waye, M. M. Y., & Bishop, D. V. M. (2012). The Genetic and Environmental Foundation of the Simple View of Reading in Chinese. *PLoS ONE* 7(10), e47872. doi:10.1371/journal.pone.0047872
- Hoosain, R. (1991). *Psycholinguistic implications for linguistic relativity: A case study of Chinese*: Psychology Press.
- Hoover, W. A., & Tunmer, W. E. (1993). 1 The Components of Reading. In G. B. Thompson, W. E. Tunmer, & T. Nicholson (Eds.), *Reading acquisition processes*. Adelaide, South Australia: Multilingual Matters.
- Hu, C.-F., & Catts, H. W. (1998). The role of phonological processing in early reading ability: What we can learn from Chinese. *Scientific Studies of Reading*, 2(1), 55-79.
- Hurford, J. R. (1991). The evolution of the critical period for language acquisition. *Cognition*, 40(3), 159-201.
- Imaizumi, Y. (2003). A comparative study of zygotic twinning and triplet rates in eight countries, 1972–1999. *Journal of biosocial science*, 35(02), 287-302.
- Keenan, J. M., Betjemann, R. S., & Olson, R. K. (2008). Reading comprehension tests vary in the skills they assess: Differential dependence on decoding and oral comprehension. *Scientific Studies of Reading*, 12(3), 281-300.
- Keenan, J. M., Betjemann, R. S., Wadsworth, S. J., DeFries, J. C., & Olson, R. K. (2006). Genetic and environmental influences on reading and listening comprehension. *Journal of Research in Reading*, 29(1), 75-91.
- Kirby, J. R., & Savage, R. S. (2008). Can the simple view deal with the complexities of reading? *Literacy*, 42(2), 75-82.
- Kovas, Y., Hayiou-Thomas, M. E., Oliver, B., Dale, P. S., Bishop, D. V. M., & Plomin, R. (2005). Genetic Influences in Different Aspects of Language Development: The Etiology of Language Skills in 4.5-Year-Old Twins. *Child development*, 76(3), 632-651.
- Leach, J. M., Scarborough, H. S., & Rescorla, L. (2003). Late-emerging reading disabilities. *Journal of Educational Psychology*, 95(2), 211-224.
- Liu, P. D., McBride-Chang, C., Wong, A. M.-Y., Tardif, T., Stokes, S. F., Fletcher, P., & Shu, H. (2010). Early oral language markers of poor reading performance in Hong Kong Chinese children. *Journal of Learning Disabilities*, 43(4), 322-331.
- McBride-Chang, C. (1995). Phonological processing, speech perception, and reading disability: An integrative review. *Educational Psychologist*, 30(3), 109-121.
- McBride-Chang, C., Cho, J.-R., Liu, H., Wagner, R. K., Shu, H., Zhou, A., . . . Muse, A. (2005). Changing models across cultures: Associations of phonological awareness and morphological structure awareness with vocabulary and word recognition in second graders from Beijing, Hong Kong, Korea, and the United States. *Journal of Experimental Child Psychology*, 92(2), 140-160.
- McBride-Chang, C., Lam, F., Lam, C., Doo, S., Wong, S. W., & Chow, Y. Y. (2008). Word recognition and cognitive profiles of Chinese pre-school children at risk for dyslexia through language delay or familial history of dyslexia. *Journal of Child Psychology*

- and Psychiatry*, 49(2), 211-218.
- McBride-Chang, C., Shu, H., Zhou, A., Wat, C. P., & Wagner, R. K. (2003). Morphological awareness uniquely predicts young children's Chinese character recognition. *Journal of Educational Psychology*, 95(4), 743.
- Metsala, J. L., & Walley, A. C. (1998). Spoken vocabulary growth and the segmental restructuring of lexical representations: Precursors to phonemic awareness and early reading ability. In J. L. M. L. C. Ehri (Ed.), *Word recognition in beginning literacy* (pp. 89-120). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.
- Nation, K., & Norbury, C. F. (2005). Why Reading Comprehension Fails: Insights From Developmental Disorders. *Topics in Language Disorders*, 25(1), 21-32.
- Neale, M. C., Boker, S. M., Xie, G., & Maes, H. H. (2006). Mx: Statistical modeling (7th ed.). Available from VCU, Department of Psychiatry, Box 900126, Richmond, VA 23298.
- Oakhill, J. V., Cain, K., & Bryant, P. E. (2003). The dissociation of word reading and text comprehension: Evidence from component skills. *Language and Cognitive Processes*, 18(4), 443-468.
- Olson, R. K., Keenan, J. M., Byrne, B., Samuelsson, S., Coventry, W. L., Corley, R., . . . Pennington, B. F. (2011). Genetic and environmental influences on vocabulary and reading development. *Scientific Studies of Reading*, 15(1), 26-46.
- Peterson, R. L., McGrath, L. M., Smith, S. D., & Pennington, B. F. (2007). Neuropsychology and genetics of speech, language, and literacy disorders. *Pediatric Clinics of North America*, 54(3), 543-561.
- Purcell, S. (2002). Variance components models for gene-environment interaction in twin analysis. *Twin Research*, 5, 554-571.
- Roberts, T. A. (2005). Articulation accuracy and vocabulary size contributions to phonemic awareness and word reading in English language learners. *Journal of Educational Psychology*, 97(4), 601.
- Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, 96(4), 523-568.
- Shu, H., McBride-Chang, C., Wu, S., & Liu, H. (2006). Understanding chinese developmental dyslexia: Morphological awareness as a core cognitive construct. *Journal of Educational Psychology*, 98(1), 122.
- So, L. K. (1993). *Cantonese Segmental Phonology Test [kit]*: Bradford Publishing Company.
- Speer, S. (2005). Introduction: Feminism, discourse and conversation analysis. In Susan A. Speer, *Gender talk: Feminism, discourse and conversation analysis*, (pp. 7-8). London New York: Routledge.
- Sticht, T. G., & James, J. H. (1984). Listening and reading. *Handbook of reading research*, 1, 293-317.
- Stromswold, K. (2001). The Heritability of Language: A Review and Metaanalysis of Twin, Adoption, and Linkage Studies. *Language*, 77(4), 647-723.
- Tsao, F.-M., Liu, H.-M., & Kuhl, P. K. (2004). Speech perception in infancy predicts language development in the second year of life: A longitudinal study. *Child development*, 1067-1084.
- Walley, A., Metsala, J., & Garlock, V. (2003). Spoken vocabulary growth: Its role in the development of phoneme awareness and early reading ability. *Reading and Writing*, 16(1-2), 5-20.
- White, B., & Kirby, J. (2007). *Depth of processing: Its relation to reading comprehension, component skills and cognitive processes*. Paper presented at the Poster presented at the annual conference of the Society for the Scientific Study of Reading, Prague, Czech Republic.
- Yeung, P.-s., Ho, C. S.-h., Chan, D. W.-o., Chung, K. K.-h., & Wong, Y.-k. (2013). A model of

reading comprehension in Chinese elementary school children. *Learning and Individual Differences*, 25, 55-66.

Yeung, P.-s., Ho, C. S.-h., Chik, P. P.-m., Lo, L.-y., Luan, H., Chan, D. W.-o., & Chung, K. K.-h. (2011). Reading and spelling Chinese among beginning readers: What skills make a difference? *Scientific Studies of Reading*, 15(4), 285-313.

Table 1

Mean Raw Scores (and Standard Deviations) of the Measures by Sex and by Zygosity, and the Intra-class Twin Correlations

Measure (Max.)	Mean (SD)					Correlation	
	Full sample	MZ		DZ		MZ	DZ
		F	M	F	M		
Speech perception (24)	19.39 (4.12)	20.14 (3.81)	18.75 (4.33)	19.46 (4.62)	19.15 (3.66)	0.41	0.06
Speech production (38)	33.18 (4.10)	33.84 (3.18)	32.45 (5.04)	33.69 (3.68)	33.03 (3.41)	0.76	0.59
Phonological awareness (24)	16.35 (4.99)	16.77 (4.84)	15.74 (5.38)	16.64 (4.64)	16.69 (4.40)	0.65	0.35
Phonological memory (124)	74.86 (26.34)	76.35 (26.59)	73.23 (26.72)	75.24 (27.73)	75.07 (23.82)	0.72	0.57
Vocabulary (80)	57.53 (15.21)	58.65 (14.03)	56.18 (16.51)	57.69 (14.89)	58.09 (14.72)	0.72	0.35
Morphological awareness (44)	24.39 (11.97)	25.65 (11.69)	23.42 (12.53)	24.38 (11.88)	23.71 (11.14)	0.61	0.29
Chinese word reading (198)	100.32 (60.70)	106.46 (61.14)	96.08 (62.13)	103.12 (59.74)	94.16 (55.73)	0.91	0.59

Note. All correlation coefficients were significant at $p < .001$ except that of speech perception for DZ ($p > .05$) and morphological awareness for DZ ($p < .01$).

Table 2.

Univariate ACE models comparisons

Baseline model	Comparison	ep	minus2LL	df	AIC	diffLL	diffdf	p
Chinese Word Reading								
1. ACE with age and gender	-	10	404.3524	732	-1059.65	-	-	-
2. ACE with age and gender	Dropping Age	8	999.5728	734	-468.427	595.2204	2	0.000
3. ACE with age and gender	Dropping Gender	7	407.1661	735	-1062.83	2.813707	3	0.421
Speech								
1. ACE with age and gender	-	10	1505.807	732	41.80707	-	-	-
2. ACE with age and gender	Dropping Age	8	1720.945	734	252.9447	215.1376	2	0.000
3. ACE with age and gender	Dropping Gender	7	1520.972	735	50.9721	15.16503	3	0.002
Phonological Skills								
1. ACE with age and gender	-	10	1330.704	732	-133.296	-	-	-
2. ACE with age and gender	Dropping Age	8	1596.093	734	128.0928	265.3893	2	0.000
3. ACE with age and gender	Dropping Gender	7	1332.032	735	-137.968	1.328033	3	0.722
Semantic Skills								
1. ACE with age and gender	-	10	903.265	732	-560.735	-	-	-
2. ACE with age and gender	Dropping Age	8	1389.86	734	-78.1398	486.5952	2	0.000
3. ACE with age and gender	Dropping Gender	7	908.9691	735	-561.031	5.704101	3	0.127

Table 3

Estimates of β_{Age} , Genetic (a^2), Shared Environmental (c^2), and Unique Environmental (e^2) Contributions to the Variance of the Four Measured Skills with 95% Confidence Intervals.

	β_{Age}	a^2	c^2	e^2
Speech				
Age as linear regressor ACE*	.32	.40 [.15, .77]	.29 [.06, .67]	.31 [.26, .37]
Quadratic residual		.51 [.19, .70]	.13 [.00, .43]	.36 [.30, .43]
Phonological skills				
Age as linear regressor ACE	.35	.28 [.07, .57]	.49 [.19, .68]	.24 [.20, .29]
Quadratic residual		.34 [.10, .68]	.40 [.06, .63]	.27 [.22, .32]
Semantic skills				
Age as linear regressor ACE*	.43	.50 [.13, .40]	.28 [.03, .31]	.21 [.09, .12]
Quadratic residual		.59 [.32, .79]	.16 [.00, .43]	.24 [.20, .29]
Chinese Word reading				
Age as linear regressor ACE	.45	.56 [.38, .82]	.35 [.09, .54]	.08 [.07, .10]
Quadratic residual		.62 [.42, .90]	.28 [.00, .48]	.09 [.08, .12]

*CI based on log likelihood was not available, standard error based CI was used instead

Table 4

Multivariate Analyses on the Genetic and Environmental Influences on Speech, Phonological Skills, Semantic Skills, and Word Reading.

	A1	A2	A3	A4
Speech	0.70*** (0.45,0.95)			
Phonological skills	0.46** (0.16,0.76)	0.37 (-0.03,0.77)		
Semantic skills	0.63*** (0.33,0.93)	0.18 (-0.40,0.77)	0.38* (0.02,0.74)	
Word reading	0.42** (0.15,0.70)	0.24 (-0.25,0.72)	-0.02 (-0.53,0.48)	0.61*** (0.42,0.81)
	C1	C2	C3	C4
Speech	0.39 (-0.04,0.82)			
Phonological skills	0.34 (-0.19,0.88)	0.53** (0.19,0.86)		
Semantic skills	0.11 (-0.46,0.69)	0.29 (-0.10,0.69)	0.29 (-0.21,0.78)	
Word reading	-0.31 (-1.04,0.42)	0.36 (-0.36,1.08)	0.16 (-1.08,1.39)	0.20 (-1.43,1.84)
	E1	E2	E3	E4
Speech	0.60*** (0.55,0.65)			
Phonological skills	0.05 (-0.01,0.11)	0.51*** (0.47,0.55)		
Semantic skills	0.03 (-0.03,0.09)	0.06* (0.01,0.12)	0.49*** (0.45,0.53)	
Word reading	0.01 (-0.02,0.05)	0.05* (0.01,0.08)	0.04* (0.01,0.08)	0.30*** (0.28,0.33)

Note. 95% confidence intervals are in parentheses. * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 5

Model Fit Statistics.

Model	-2LL	NPAR	ΔX^2	Δdf	P (Δ)
1. Cholesky model	5773	34	-	-	-
2. Model 1	5776	28	3.14	6	.792
3. Model 2	5791	29	18.12	5	.003
4. Model 3	5788	29	15.31	5	.009
5. Model 4	5782	30	9.70	4	.046
1. Model 1 (ACE)	5776	28	-	-	-
2. Model 1 (AE)	5812	20	36.24	8	<.001

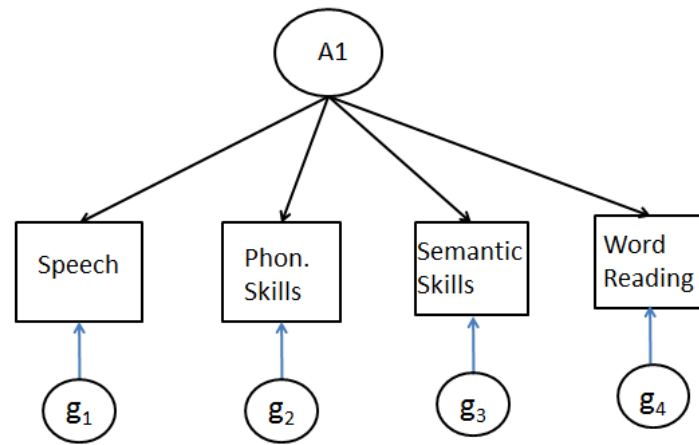
Table 6

Genetic (above diagonal) and Shared Environmental (below diagonal) Correlations among the Three Composite Scores and Chinese Word Reading (95% confidence intervals are presented in parentheses).

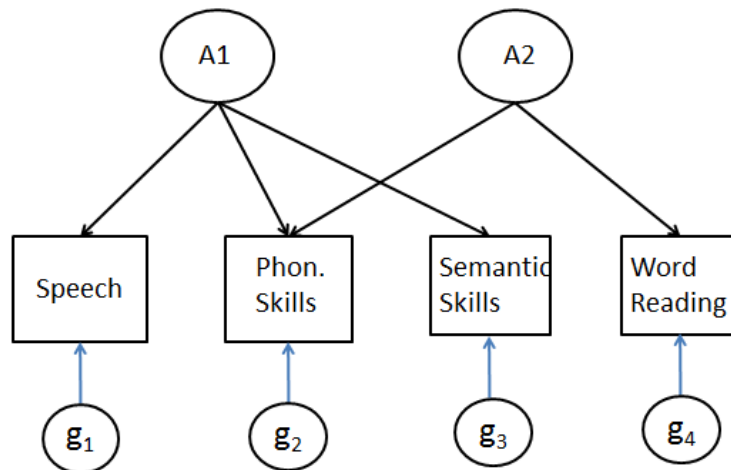
	Speech	Phonological skills	Semantic skills	Word reading
Speech	-	.78 (0.34,1.00)	.83 (0.54,1.00)	.54 (0.19,0.87)
Phonological skills	.55 (-0.89,1.00)	-	.80 (0.45,1.00)	.61 (0.26,0.93)
Semantic skills	.27 (-1.00,1.00)	.72 (-1.00,1.00)	-	.51 (0.24,0.73)
Word reading	-.58 (-1.00,0.49)	.24 (-0.79,0.73)	.50 (-1.00,1.00)	-

Figure 1. Four models delineating different genetic factor models connecting speech and reading.

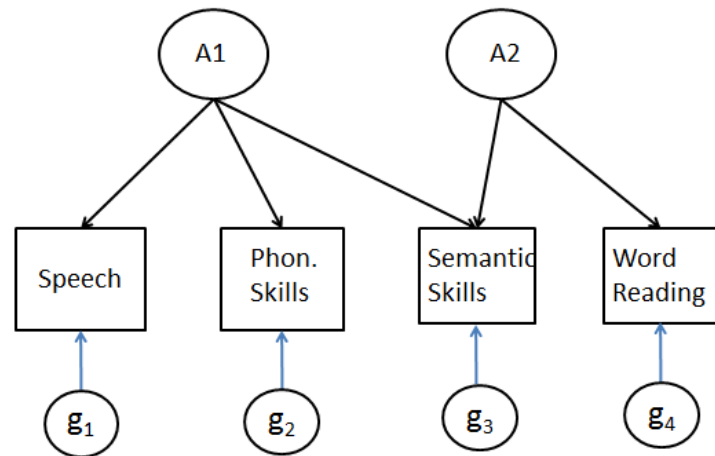
Model 1: Single common genetic factor



Model 2: Phonological pathway link



Model 3: Semantic pathway link



Model 4: Separate genetic factors for speech & reading

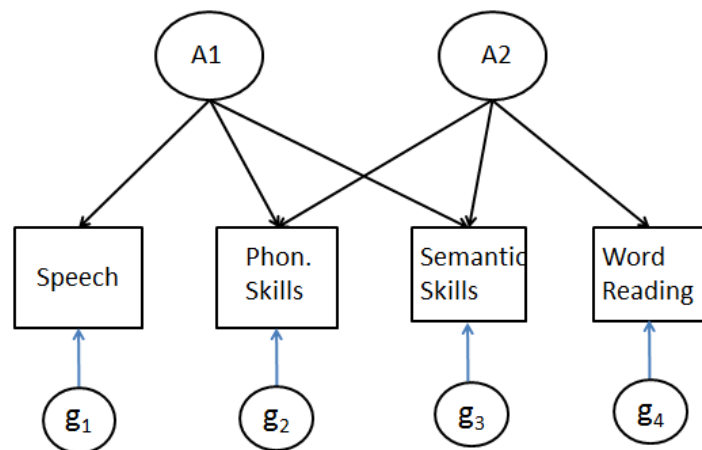


Figure 2. Genetic component of the Cholesky decomposition model for speech, phonological skills, semantic skills, and word reading.

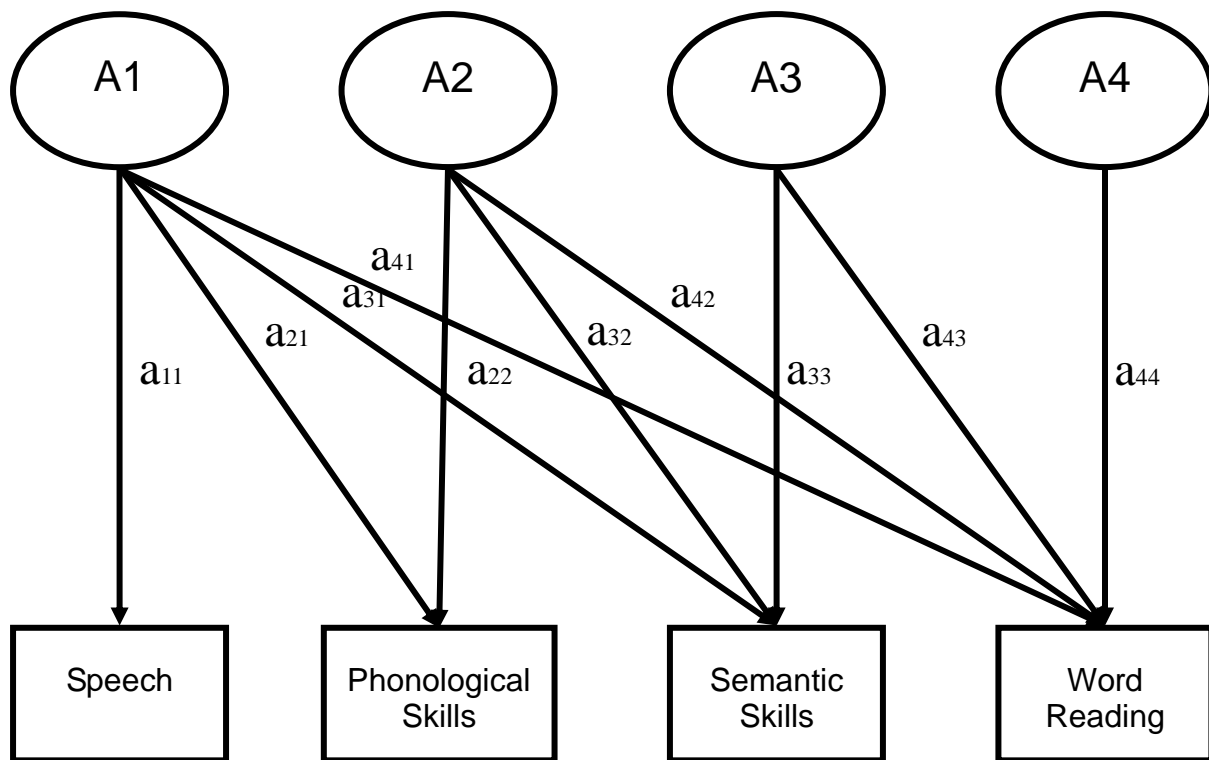


Figure 3. Standardized path estimates of Model 1.

