Exploring the genetic and environmental etiologies of phonological awareness, morphological awareness, and vocabulary among Chinese-English bilingual children: The moderating role of second language instruction

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Abstract

This study investigated the associations among bilingual phonological awareness, morphological awareness, and vocabulary by focusing on their genetic and environmental etiologies. It also explored the influence of family socio-economic status (SES) and language exposure amount on the genetic and environmental effects. A twin study was conducted with 349 pairs of Chinese-English bilingual twins (mean age=7.37 years). Cross-language transfer was found in phonological and morphological awareness but not in vocabulary knowledge. A common genetic overlap was found among these bilingual abilities. We also found a common shared environmental effect that may account for the cross-language transfer in phonological awareness and the associations among English abilities. SES and language exposure were significant environmental influences on bilingual phonological awareness and English vocabulary. More teaching in Chinese was related to a stronger genetic effect on Chinese morphological awareness, whereas more teaching in English was related to a stronger environmental impact on English abilities.

Key words: phonological awareness; morphological awareness; vocabulary; first language; second language; twin study design

Introduction

Vocabulary and metalinguistic skills such as phonological awareness and morphological awareness are essential predictors of children's literacy development (e.g., McBride-Chang et al. 2006; Wang et al. 2009). Phonological and morphological awareness are linked with vocabulary acquisition and growth in both monolinguals and bilinguals (Hsu et al. 2019; McBride-Chang et al. 2006; Metsala 1999; Sparks and Deacon 2015). However, the underlying mechanism of their associations remain unclear. In addition, a number of studies have shown that phonological and morphological awareness in native language (L1) were associated with the corresponding abilities in second language (L2), suggesting that phonological and morphological awareness can be transferred across languages. This is in line with the interdependence hypothesis arguing that language skills can be transferred across languages (Cummins 1979). According to this theoretical hypothesis, the cross-language transfer is underpinned by a common learning mechanism supporting the acquisition of both L1 and L2. However, the nature of the common learning mechanism remains largely unknown. Genetic and environmental factors can be important influences of our cognition and can explain observed links between different abilities (Neale and Maes, 2004). Therefore, exploring the genetic and environmental etiologies of bilingual language abilities may advance our understanding of the nature of the underlying mechanisms supporting cross-language transfer.

However, simply exploring the importance of genetic as opposed to environmental contributions is not adequate for understanding complex human abilities because genetic contributions are likely to vary as a function of environmental influence (Purcell 2002). According to the bioecological model, a supportive environment can facilitate the actualization of genetic potential, thus leading to larger genetic effect on an ability (Bronfenbrenner and Ceci 1994). On the other hand, the diathesis-stress model dictates that an unfavorable environment could be a stressor that renders deleterious genes more likely to appear. Identifying essential environmental factors influencing bilingual development and investigating their potential effects on genetic and environmental contributions to bilingual abilities is important. Such a focus not only advances our scientific understanding of how language ability is affected by the interaction of heritability and environment, but it may also lead to more effective instructional programs to optimize these environmental factors in order to promote bilingual language learning. Family socioeconomic status (SES) and language exposure are likely to be important environmental factors for bilingual development (Quiroz et al. 2010; Vernon-Feagans et al. 2012) and, hence, may significantly mediate the environmental effects and moderate the genetic effects on bilingual abilities. However, there is a lack of study exploring such mediating and moderating effects of SES and language exposure.

With this research background, in the present study, we investigated the biological and environmental etiologies of bilingual phonological awareness, morphological awareness, and vocabulary. We further explored the mediating and moderating effects of SES as well as language exposure at home and school on the genetic and environmental contributions to bilingual abilities. These investigations were conducted via a twin study (e.g., Neale and Maes 2004).

Phonological awareness, morphological awareness, vocabulary, and cross-language transfer

According to Cummins' (1979) interdependence hypothesis, language skills can be transferred across languages. A number of studies have shown that phonological awareness and morphological awareness in L1 are correlated with the corresponding skills in L2 even between highly contrasted language pairs such as the Chinese-English pair (e.g., Chung et al. 2019; Wang et al. 2009), suggesting that phonological awareness and morphological awareness are likely to be transferred across languages. The studies regarding instructional intervention programs provide even stronger evidence of cross-language transfer in phonological awareness (Chung et al. 2019). For example, Chen et al. (2010) found that Chinese Grade 1 primary school children who received more intensive English instruction performed better in both English and Chinese phonological awareness tasks relative to their counterparts who received less intensive English instruction. Wise et al. (2016) found that children who were at-risk readers improved their French phonological awareness after receiving training in English phonological awareness and letter-sound correspondence. The interdependence hypothesis further argues that a common underlying mechanism supports the learning of both L1 and L2 (Cummins, 1979). To advance our knowledge of that mechanism, it is necessary to explore the genetic and environment foundations of bilingual language skills.

Family socio-economic status (SES) and language exposure as environmental influences on language development

Children's bilingual language development is affected by diverse contextual factors, especially SES as well as home and instructional languages (e.g., Altinkamis and Simon 2020; Vernon-Feagans et al. 2012). SES is usually measured through a combination of parents' education levels and family income. Numerous studies have shown that children in families with high SES are more likely to perform better on language tasks in L1 and L2 (e.g., Bonifacci et al. 2020; Chow et al. 2017; Howard et al. 2014). Altinkamis and Simon's (2020) study further suggested that mother's education level affects children's L2 skills to a larger extent relative to L1.

The importance of language exposure in language development is suggested by the time-on-task hypothesis: More exposure to one language usually leads to larger vocabulary volume of that language, which, in turn, leads to less exposure to and smaller vocabulary volume in another language (Quiroz et al. 2010). Several studies exploring the link between L1 and L2 vocabulary have shown a negative correlation between the two and even reported that bilingual children scored lower on vocabulary in L1 relative to their monolingual counterparts (Bialystok et al. 2005; Tabors et al. 2003). Patterson's (2002) study showed that the association between amount of language exposure and vocabulary size is language-specific. These findings support the time-on-task hypothesis. Furthermore, existing studies indicate that exposure to L2 also facilitates the development of other language skills such as phonological and morphological skills (Cabrera et al. 2019; Nance 2020; Paradis 2010). If L2 is used more as a home language and instructional language at school, children are more likely to achieve higher scores in general L2 skills (Altinkamis and Simon 2020; Howard et al. 2014). Therefore, it could be that language exposure is an important common environmental influence on language skills.

Twin studies and language abilities

Twin studies are often designed to understand genetic versus environmental contributions to a specific trait (e.g., Neale and Maes 2004) and, therefore, such studies are an appropriate research method for investigating the underlying biological and environmental influences supporting the associations among bilingual language measures. Identical twins and fraternal twins both share almost the same family and school environments. The similarity of the genes between identical twin is up to nearly 100%, whereas that between fraternal twin is about 50% (Neale and Maes 2004). If the covariance on a trait in identical twin pairs is higher than in fraternal twin pairs, genetic effects (A) on that trait are often suggested. If covariance in identical twin pairs is similar in magnitude to that in fraternal twin pairs, shared environmental effects (C) could be suggested. Covariance between identical twin pairs smaller than 1.0 could result from non-shared environmental effects (E). By setting A, C, and E as latent variance components and by comparing the covariance in a trait between identical and fraternal twin pairs in a statistical model, we can estimate the proportion of the trait variance accounted for by A, C, and E. In addition, multivariate genetic analyses such as Cholesky decomposition allow us to investigate the genetic and environmental links among 2 or more traits by breaking down covariance among traits into their shared and independent variance related to genetic, shared environmental, and non-shared environmental effects.

Heritability estimates of different language skills differ to a large extent. Current research in Western languages has reported that a notable proportion of phonological awareness variance is explained by genetic influences (above 40%) in young children at 6 years old or above (Hohnen and Stevenson 1999; Petrill et al. 2006). The genetic effect explaining the proportion of vocabulary ability variance prior to 5 years old is consistently found to be 20-30% and reaches 45% or higher in children aged from 6 to 8 years old (Olson et al. 2011; Rice et al. 2018). A study by Byrne et al. (2002) of preschool children reported that the variance in productive morphology explained by non-shared environment is stronger (42%) relative to shared environment (27%) and genes (31%).

Heritability estimates seem to be relatively weaker and effects of shared environment relatively stronger for phonological skills and vocabulary ability in Chinese and Japanese, at least thus far. Studies by Wong et al. (2014) and Ho et al. (2017) among preschool and primary school children reported around 50% of the individual differences in Chinese phonological awareness are accounted for by shared environment; genetic effects only accounted for about 10% of the variance in the study by Wong et al. (2014) and 28% of the variance in the study by Ho et al. (2017). In addition, Wong et al. (2014) reported that the proportion of variance in receptive vocabulary in both Chinese (L1) and English (L2) accounted for by heritability estimates was about 10% and the proportion explained by shared environment reached more than 50%. Fujisawa et al. (2013) studied Japanese 3- to 4-year-olds. These authors reported even lower heritability estimates in phonological awareness (0%) and receptive vocabulary (7%). Regarding Chinese morphological awareness, a study in children aged from 3 to 11 reported percentages of variance explained by heritability estimates, shared environment, and non-shared environment to be, respectively, 44%, 20%, and 36% (Chow et al. 2011).

Several studies have also reported genetic versus environmental overlaps among different language skills. Samuelsson et al. (2005) found strong genetic and environmental associations among general verbal ability, phonological awareness, and print knowledge. Ho et al. (2017) reported that the links among speech, phonological skills, semantic skills, and word reading in Chinese were mainly out of a common genetic factor. Wong et al. (2014) found that the Chinese-English transfer in phonological awareness and receptive vocabulary stem from both genetic and shared environmental overlaps. A recent study in adolescents by Erbeli et al. (2020) showed that both genetic and shared environmental correlations between reading comprehension and print exposure were significant, though the genetic correlation was stronger. These findings suggest that the associations demonstrated among different language abilities occur potentially from both genetic and environmental overlaps. However, it remains unclear whether the links among bilingual phonological awareness, morphological awareness, and vocabulary abilities predominantly emerge from common genetic or environmental impacts.

The twin study design can also be used to examine to what extent an identified shared environmental factor (F) meditates the variance in the total shared environmental effect (C) on an ability by considering F as one subset of C (See Figure 1) (Petrill et al. 2004). SES is usually the same for a pair of twins and, thus, can be regarded as an identified shared environment factor (F) (Petrill et al. 2004). Petrill et al. (2004) reported that SES accounted for 3-4% of the variance in parent-rated vocabulary and verbal skills and mediated 5-6% of the variance in the shared environmental effect in these skills in 3- to 4-year-olds. Chow et al. (2017) found that SES explained 2-6% variance in different language skills and mediated 12-16% of shared environmental influences.

Environmental factors may also affect genetic contributions of a trait (Purcell 2002). Purcell (2002) proposed a Gene-Environment interaction (G×E) model that can detect whether heritability estimates vary as a function of an identified environmental factor which is a moderator, by regressing the genetic effect on that moderator. Only a few studies have looked into whether SES moderates the genetic effect on language skills. A study by Rowe et al. (1999) of 16-year-old non-Hispanic White and African American twins demonstrated a higher proportion of heritability estimates in vocabulary size among those whose parents had higher levels of education, supporting the bioecological model (Bronfenbrenner and Ceci 1994). Studies by Friend et al. (2008, 2009) of American children found that heritability estimates of both low and high reading ability were augmented with lower levels of parental education. However, the studies conducted outside of the U.S. did not demonstrate that SES moderates the genetic effect on general language and literacy abilities (Chow et al. 2017; Grasby et al. 2019).

In addition to SES, other important environmental factors that potentially impact language abilities have been explored in twin studies relatively rarely. Language exposure is likely to be a critical environment influence on language development (Altinkamis and Simon 2020; Howard et al. 2014). Therefore, it is necessary to explore to what degree L1 versus L2 exposure at home and school mediates the shared environmental effect and moderates the genetic effect on language abilities.

The present study

This study aims to explore the genetic and environmental etiology of phonological awareness, morphological awareness, and vocabulary across L1 and L2 to advance our understanding of the underlying mechanism supporting cross-language transfer and the connections among these language abilities. It further considers the mediation and moderation of SES as well as the amount of L2 exposure at home and school on the genetic and environmental contributions of these language abilities.

There are four research questions. First, to what degree does heritability as opposed to environment contribute to bilingual phonological awareness, morphological awareness, and vocabulary? We hypothesized that heritability versus environmental factors contributes to these bilingual abilities to varying degree. We anticipated that bilingual phonological awareness and vocabulary would be more strongly affected by environmental effects relative to heritability estimates. This hypothesis was made based on the existing findings regarding genetic versus environmental contributions to language abilities in Chinese children (Ho et al. 2017; Wong et al. 2014).

Second, to what extent do SES and amount of reported use of L2 at home and school affect L1 relative to L2 abilities and mediate their shared environmental influence? Based on the existing findings showing the importance of SES and language exposure in bilingual development (e.g., Altinkamis and Simon 2020; Bonifacci et al. 2020), we predicted that the shared environmental effects on all these bilingual abilities are mediated by SES and the amount of L2 use, which affects L2 more strongly than L1. According to the time-on-task hypothesis, we anticipated that the mediating effect of the amount of L2 use is especially strong on L2 vocabulary.

Third, do SES and the amount of usage of L2 at home and school moderate the genetic and environmental contributions to these bilingual abilities? If so, how? Higher SES represents a more facilitative environment. More L2 usage at home and school is more facilitative for L2 development but may be less facilitative for L1 development. If a genetic effect is larger in a more facilitative environment, the bioecological model (Bronfenbrenner and Ceci 1994) is supported. On the other hand, if the genetic effect is larger in less facilitative environments, the diathesis-stress model (Scarr 1992) is supported. If no moderating effect of SES or L2 usage is indicated, heritability estimation of the bilingual abilities may not be affected by these environmental factors. Given that the twin studies conducted outside of the U.S. have predominantly showed no moderating effect of SES on genetic contributions to language and cognitive abilities (e.g., Chow et al. 2017; Grasby et al. 2019; Tucker-Drob and Bates 2016), we predicted that SES does not moderate the heritability estimation of the bilingual abilities in our study. We did not have specific prediction about the moderating effect of L2 exposure on genetic effects as there is a lack of such findings.

Last and most important, do the associations among bilingual phonological awareness, morphological awareness, and vocabulary abilities predominantly emerge from a common genetic or environmental overlap? This research question aims to advance our understanding of the nature of the common underlying mechanism that supports cross-language transfer identified in the interdependence hypothesis. Based on the relevant existing findings (Ho et al. 2017; Samuelsson et al. 2005; Wong et al. 2014), we posited that the associations among these bilingual abilities are mainly based on a common genetic foundation.

Method

Participants

The participants were 349 pairs of Chinese Cantonese-speaking twins aged from 5.92 to 10.08 years old (mean age=7.33, SD=0.87) in Hong Kong. Among the 142 pairs of monozygotic twins (MZ), 75 pairs were female. Among the 207 pairs of dizygotic twins (DZ), 48 pairs were female, 59 pairs were male, and the rest were opposite sex. Among these 698 participants, 384 were in Grade 1, 189 in Grade 2, and 125 in Grade 3. All participants were recruited through school invitation by phone calls or friend and family referrals. These children typically entered primary school at around age 6, and they were introduced to reading in Chinese and simple English as a second language from around age 3 when they started kindergarten.

Measures

Chinese phonological awareness

A task with syllable deletion and onset phoneme deletion items developed in a previous study (Chung et al. 2008) was used. In this task, all the items were organized in 6 blocks according to difficulty levels from P0 (designed for preschoolers) to P5 (designed for Grade 5 Primary students). Children started with a block in line with their school grade. If they answered incorrectly to more than 1 item in the block, they were then presented with items of a lower grade difficulty. According to the basal rule, if they answered all the items correctly or committed only one error in the block, they were given full marks for the preceding blocks. According to the ceiling rule, if the participants answered 5 or more items incorrectly within one block and they had completed all the P0 level items, the task was terminated. The words or non-words used in this task were pre-recorded by a native Cantonese speaker. The participants were required to repeat the stimulus (word or non-word) directly following the presentation of it.

The syllable deletion section, with 4 practice and 19 test items, was designed for P0 and P1 levels. Children were asked to delete one syllable from the stimulus, either at the initial, middle, or final position, according to the requirement. A mixture of tri-syllabic words and non-words were used. The more difficult onset phoneme deletion part, with 4 practice and 22 test items, was designed for P2 to P5 levels. Children were required to delete the onset phoneme of the stimulus. This task commenced with monosyllabic words and non-words, followed by disyllabic and tri-syllabic non-words. Each correct answer was allotted 1 point. Therefore, the maximum total score was 41.

Chinese morphological awareness

We adapted a Chinese morphological construction task including 46 items (2 for practice) originally developed in a previous study (McBride-Chang et al. 2008). Children were asked to combine the morphemes orally presented to them to form novel compound words. For example, a child was informed that a bracelet on wrists is called "手鍊" (hand bracelet) and was asked to make a new compound indicating a bracelet on feet (namely, "腳鏈" foot bracelet). One point was given for each correct answer and the maximum total score was 44.

Chinese vocabulary knowledge

This task was comprised of 3 sections and was used in previous studies (e.g., Tong et al. 2018). Section 1 tested Chinese receptive vocabulary (10 items). Children were orally presented with a word and 4 pictures, and they were required to point to the picture corresponding to the word meaning. Section 2 tested expressive vocabulary and included 12 items. Children were asked to orally name a given picture in Chinese, including objects (e.g., 飛機, "airplane") and actions (e.g. 漏水 "dripping"). The pictures were adopted from the Peabody Picture Vocabulary Test – Third Edition (PPVT-III; Dunn and Dunn 1997).

The last section included 26 items on Chinese vocabulary definitions. Children were orally presented a word and were required to explain the word. They could describe it in various ways including what it is, how it is done, or what they can do with it. The items included objects (e.g., 刀 "knife"), places (e.g. 公園 "park") and adjectives (e.g. 誠實 "honest"). If their responses were too simple or short, the experimenter encouraged them to elaborate on their answers.

In all of the sections, the difficulty levels gradually increased. Each correct answer in the first two sections carried 1 point, and the score for each answer in the last section ranged from 0-2 depending on the precision of the answer. Therefore, the maximum total score of this test was 74.

English invented spelling

Because there is sometimes a floor effect in English phonemic awareness tasks among Hong Kong Chinese children (e.g., McBride-Chang and Ho 2005), we selected an alternative method for measuring English phonemic sensitivity: invented spelling in English. This task, which assesses the letter-sound association and the underlying phonological structure of a word, was used as a good alternative way to assess Chinese young children's English phonological skills (McBride-Chang and Ho 2005).

In this task, 12 non-words (e.g. wam) were prerecorded by a native English speaker. Children were asked to write down the spelling of the stimulus right after the oral presentation to them. All the stimuli are monosyllabic and contain 3 or 4 phonemes. The scoring of this task was based on whether the spelling matched the phonological rules in English. We applied the scoring scheme developed by Mann et al. (1987). A 5-point scale was used to score each item, and the maximum total score was 60.

English morphological awareness

We adapted an English morphological construction task including 4 practice and 20 test items from a test originally developed among native English-speaking children (McBride-Chang et al. 2005). Similar to the Chinese morphological construction task, children were asked to produce orally novel English compounds by combining the morphemes presented to them. In addition, 4 of these items assess the production of plural forms and verbs in correct tenses. Each correct answer merited 1 point, and the maximum total score was 20 points.

English vocabulary knowledge

This task consisted of 3 sections with each containing 15 items and has been used in previous studies (Tong et al. 2018). Similar to the Chinese one, it tested receptive vocabulary (15 items), expressive vocabulary (15 items), and vocabulary definition (15 items). The difficulty levels increased gradually. The scoring method was the same as the parallel task for Chinese. The maximum total score was 60.

Background Questionnaire

We collected demographic background information from participants' parents, including father's and mother's education levels (7-point scales; *1 = Secondary 3 or below, 2 = Secondary 4 to 5, 3 = Secondary 6 to 7, 4 = Associate degree, 5 = Bachelor's degree, 6 = Master's degree,* and *7 = Doctorate degree*), household monthly income (6-point scales from *1 = HK$10,000 or below, 2 = HK$10,001-20,000, 3 = HK$20,001-30,000, 4 = HK$30,001-40,000, 5 =HK$40,001-50,000*, and *6 = HK$50,001 or above*), and twins' use of English at home (4-point scales from

1=Never to *4=Always*). Parents' answers to these questions applied to both the twins. No parent reported to us that his/her twin children's home English use frequency corresponded to different scales. In addition, the twins in the same family went to the same school, and parents were asked to write down the respective percentage of English and Chinese (the sum of the two was 100%) used in teaching in their children's schools. In Hong Kong, the curricula and instructional languages in the same school were usually the same across classrooms; therefore, no matter whether a pair of twins was in the same or different classrooms, the proportion of teaching in English was almost the same for them.

Procedure

A saliva sample with DNA kit of each participant was collected for zygosity testing to determine whether the twins were monozygotic or dizygotic. The language tests were administered at participants' homes by trained experimenters, and the instructions were all in Chinese.

Behavior genetic analyses

The OpenMx package (Neale et al. 2016) in R (R Core Team 2013) was used to perform the behavior genetics analyses. All models were fit to the raw data using the Full Information Maximum Likelihood option in OpenMx (Neale et al. 2016). Participants' age was controlled for in these analyses as a covariate. We first conducted sex-limitation univariate models on all the phenotypes but did not find any significant gender differences in explaining the phenotypes by additive genetics (A), shared environment (C), and non-shared environment (E) factors. We then conducted a univariate model adapted from Petrill et al. (2004) (Figure 1) to understand the approximate proportion of the phenotypes explained by identified shared environment (F) factors along with A, C, and E. SES, home and school English use were the F factors in this study. The total proportion explained by shared environment is the sum of C and F factors. This analysis was used to test the hypotheses related to the first and second research questions.

We also adopted the G×E model (Purcell 2002), where the A, C, and E main effects are supplemented by considering the moderating effect (see Figure 2 for detail). The moderators were SES, home and school English use in this study. Unstandardized results are reported as standardized solutions usually lose considerable information in reference to the source of variance (Purcell 2002). We compared the model fit of the full moderator model with that after dropping one specific moderating effect to see if the dropped moderating effect was significant. This analysis was used to explore the third research question.

Finally, the Cholesky decomposition model (Figure 3) was used to investigate the genetic and environmental associations of the phenotypes in order to test the last hypothesis. The order of the phenotypes was 1. Chinese phonological awareness, 2. Chinese morphological awareness, 3. Chinese vocabulary knowledge, 4. English invented spelling, 5. English morphological awareness, and 6. English vocabulary knowledge). Figure 3 shows the example of the model on genetic variance. The model decomposes the genetic variance of multiple phenotypes into separate components of A1 to A6. It assumes that the latent factor A1 is the sole effect on Chinese phonological awareness and it also partially explains the other five phenotypes. A2 accounts for the residual variance in Chinese morphological awareness not shared with Chinese phonological awareness, and it also partially accounts for the remaining four phenotypes. A3 to A5 can be explained in the similar manner. We also used multivariate analysis to investigate the correlations among all the phenotypes in reference to genetic and environmental effects.

Results

Descriptive statistics and correlations

Descriptive statistics of the participants' performance on all the tests and parents' responses to the background question are presented in Table 1. The language tests used in this study all had good internal consistency reliability as indicated by the Cronbach alpha values of .80 or above (Cortina 1993). We computed the intra-class twin partial correlations for MZ and DZ respectively (controlling for age) and found that the correlation coefficients in MZ were higher than those in DZ on all the tasks. This may indicate the presence of genetic influences. As the difference between MZ and DZ intra-class correlations was especially large in Chinese morphological awareness, possibly indicating the presence of a dominant genetic influence on Chinese morphological awareness.

To analyze the relationships among all the measures, we conducted partial correlations controlling for age (Table 2). Father's and mother's education levels, and household income were highly correlated (r>.60); therefore, we computed the composite score of SES by performing principal component analysis on the three variables and using the first principal component. This is one typical way to reduce dimensionality in multivariate data and to develop a composite score (e.g., Kolenikov and Angeles 2008). Because of the high intra-class correlations on the language measures within twin pairs, the sample size and magnitude of data patterns could be inflated if the performance scores of both the twin children were used for quantitative analyses (e.g., Chow et al. 2013). Therefore, we randomly selected the performance scores of one child of each twin pair for the partial correlations controlling for age. As can be seen, SES was positively correlated with all the language measures except for Chinese vocabulary knowledge (rs≥.20, p<.01). Home and school English use was positively correlated with Chinese phonological awareness (rs≥.22, p<.01) and English invented spelling and vocabulary (rs≥.25, p<.01); in contrast, home English use was negatively correlated with

Chinese vocabulary (r=-.15, p=.05). Chinese phonological and morphological awareness, English invented spelling, and morphological awareness were positively correlated with one another ($rs \geq .46$, $p<.01$). Chinese and English vocabulary abilities were respectively positively correlated with all the Chinese and English meta-linguistic measures ($rs \geq .22$, $p<.01$); however, the vocabulary abilities in the two languages did not correlate with each other.

Univariate behavioral genetic analyses

Table 3 shows the results of univariate behavioral genetic analysis. Heritability estimates explained around 24% variance in Chinese phonological awareness, 41% variance in Chinese vocabulary, and 37% variance in English morphological awareness. In Chinese morphological awareness, a notable heritability estimate (about 55%) was found. The variance in English invented spelling and vocabulary explained by heritability estimates was rather small, around 12% in invented spelling, and 7% in vocabulary. The total shared environmental effect was indicated by the combination of C, SES, home English use (SEU), and school English use (SEU) in Table 3. It accounted for variance in Chinese phonological awareness up to some 46%, in Chinese vocabulary up to about 18%, and in English morphological awareness up to approximately 25%. The shared environmental effect explained strong variance in English invented spelling (about 73%) and English vocabulary (about 83%); however, it explained very little variance in Chinese morphological awareness. The effect of E was notable on Chinese morphological awareness (about 42%), Chinese vocabulary (around 41%), and English morphological awareness (about 38%). Taken together, environmental effects possibly explained around 60% variance or above in all the language abilities except for Chinese morphological awareness. As considerable heritability estimates and few shared environmental effects were found on Chinese morphological awareness, we additionally conducted a univariate model investigating the effects of A, dominant genetics (D), and E on Chinese morphological awareness to further understand the nature of its underlying etiology. We found that A, D, and E respectively explained the variance proportion of Chinese morphological awareness up to around 50%, 17%, and 32%; this also suggests the importance of heritability estimates on Chinese morphological awareness.

SES significantly explained variance in Chinese phonological awareness (11%), English invented spelling (16%), English morphological awareness (12%), and English vocabulary (32%), and mediated the total shared environmental influence on these phenotypes respectively up to around 24%, 22%, 50%, and 39%. Home and school English use significantly explained individual differences in Chinese phonological awareness, English invented spelling, and English vocabulary. They were especially important in English vocabulary, respectively explaining 21% and 14% of its variance and contributing to 26% and 17% of the total shared environmental influence on English vocabulary.

Only school English use manifested moderating effects (see Table 4 and Figure 4). Specifically, when more teaching in English at school was reported, heritability estimates significantly decreased in Chinese morphological awareness (Figure 4a), while on the other hand, the shared environmental effect on English invented spelling and vocabulary increased (Figure 4b and 4c) ($p<.05$).

Multivariate behavioral genetic analyses

The Cholesky decomposition model indicated that all these phenotypes had a common genetic foundation (A1 in Figure 3) and a common shared environmental foundation (C1) (see Table 5). Chinese vocabulary was also linked as another genetic effect with Chinese morphological awareness (A2). English vocabulary was more strongly affected by the common shared environmental effect (C1) than by the common genetic effect (A1). In addition, each of the phenotypes was uniquely affected by a non-shared environmental effect.

Table 6 shows genetic and environmental correlations. Significance of the correlations was determined via whether the lower level of 95% confidence interval was larger than .00. Chinese vocabulary did not significantly correlate with English invented spelling in heritability estimates, while the other genetic correlations were all significant. In relation to shared environmental foundation, Chinese phonological awareness correlated significantly with all the other phenotypes. English vocabulary significantly correlated with all the other phenotypes, except for Chinese vocabulary.

Discussion

The genetic relative to environmental contributions to bilingual phonological awareness, morphological awareness, and vocabulary

The univariate genetic behavioral models of the present study indicate that in Chinese children, L1 morphological awareness was substantially explained by genetic influences, while the other L1 skills (phonological awareness and vocabulary) and all L2 skills were better explained by environmental influence. These findings generally support our first hypothesis and are comparable to previous findings in Chinese-English bilingual children (Ho et al. 2017; Wong et al. 2014). They highlight the importance of environment in developing vocabulary knowledge and L2 language skills. However, compared with the findings by Wong et al. (2014), the shared environmental influence found in our study on Chinese phonological awareness and vocabulary appeared to be smaller. This could be because we used different measurements to assess these language skills and the age range in our study was much smaller than that of the study by Wong et al. In addition, compared with the study by Chow et al. (2011), our study showed an even stronger genetic influence and more negligible shared environmental influence on Chinese morphological awareness. This may also be due to the smaller age range of participants in our study. Yet both studies suggest remarkable heritability estimates in L1 Chinese morphological awareness. In addition, we found a moderate non-shared environmental influence (around 38%) on English morphological awareness, which is consistent with the findings from Byrne et al. (2002) in native English-speaking children. It appears that Chinese morphological awareness is a highly heritable skill, whereas the other language or meta-linguistic skills in Chinese children are more influenced by environment.

SES and the amount of using L2 at home and school as shared environmental factors

The partial correlations and univariate behavior genetic model show that SES was a significant shared environmental factor in all the bilingual abilities except for Chinese vocabulary. The impact of SES on L2 English vocabulary was especially strong (explained 32% of the variance).

The amount of English use at both home and school were also significant shared environmental factors in phonological skills and English vocabulary, and they especially explained a moderate amount of variance in English vocabulary (21% and 14% respectively) among the genetic and environmental factors. These results echo some previous findings showing the importance of language exposure in the development of language skills (Cabrera et al. 2019; Paradis 2010). However, home English use was negatively correlated with Chinese vocabulary although this correlation was rather weak and just reached the threshold level of significance (p=.05). This is justifiable as those who use English more often may use Chinese less often, which, in turn, adversely affects Chinese vocabulary. In addition, as suggested by the partial correlations, home language seemed to relate to bilingual vocabulary knowledge a bit more strongly relative to instructional language.

SES and the amount of exposure to English affected English vocabulary much more strongly than Chinese vocabulary. These findings echo the findings in Altinkamis and Simon's (2020) study and suggest that L2 vocabulary is especially influenced by L2 exposure and resources that children can obtain from their families (e.g., having more books and language activities) to a substantial degree. L2 is usually less developed relative to L1. Chinese primary school children may have already acquired a large amount of vocabulary knowledge in Chinese, while they still need to largely rely on exposure to English and relevant resources to develop English vocabulary. To summarize, these findings generally support our hypotheses related to the second research question and the time-on-task hypothesis (Quiroz et al. 2010).

The impact of gene-environment interaction

We found a G×E effect on Chinese morphological awareness. As the amount of reported teaching in English at school increased, heritability estimates of Chinese morphological awareness decreased (Figure 4a). Because less teaching in English at school meant relatively more teaching in Chinese in our study, this G×E on Chinese ability factor appears to support the bioecological model (Bronfenbrenner and Ceci, 1994) that more exposure to Chinese in teaching may help to actualize the genetic potential that triggers more genetic influence on Chinese morphological skill. This finding suggests that genes dominate L1 morphological skill under favorable environmental conditions.

In addition, when the amount of teaching in English was greater, the influence of shared environment on English invented spelling and English vocabulary was also higher (Figures 4b and 4c). Perhaps L2-rich environmental input may lead to larger individual differences in L2 performance caused by a shared environmental effect. It could also be that if learning L2 is emphasized in family or school, children are more likely to receive education in an L2-rich environment.

However, we did not find any moderating effects of SES and home English use on the genetic contribution to bilingual abilities. These findings, related to SES, which support our corresponding hypothesis, do not echo the findings conducted in the U.S. (Friend et al. 2008, 2009; Rowe et al. 1999) but are consistent with findings from Chow et al. (2013) obtained among Hong Kong primary school students and findings from Grasby et al. (2019), obtained among Australian students in grades 3 to 9. Grasby et al. (2019) argued that gene-environment interactions in cognitive abilities are typically found in the U.S. but not other Western countries as quality teaching and educational resources in the U.S. are more dependent on SES than in other developed countries (e.g., Darling-Hammond 2015). Perhaps, if home environment does not affect education quality and resources too much, it does not affect the genetic effect on language abilities to a notable degree.

The genetic and environmental overlap of bilingual phonological awareness, morphological awareness, and vocabulary

The results of partial correlations suggest cross-language transfer in phonological awareness and morphological awareness but not in vocabulary ability. This is consistent with the findings of previous studies (e.g., Ke and Xiao 2015; McBride-Chang et al. 2006) and supports both the interdependent hypothesis (Cummins 1979) and time-on-task hypothesis (Quiroz et al. 2010). Meta-linguistic skills are likely be transferred across languages (Cummins 1979); however, vocabulary development is predominantly influenced by the exposure amount of the specific language (Quiroz et al. 2010). In addition, in both L1 and L2, phonological awareness and morphological awareness were associated with vocabulary. This also echoes previous findings (e.g., Hsu et al. 2019; Sparks and Deacon 2015).

Results of the Cholesky model further answer the last research question and indicate that the associations found among the bilingual abilities may emerge from a common genetic and a common shared environmental foundation. However, the shared environmental correlation between L1 and L2 vocabulary was insignificant. Also, Chinese morphological awareness did not significantly correlate with Chinese vocabulary and English morphological awareness on the shared environmental effect. Taken together, these findings support our last hypothesis and suggest that there may be a common genetic factor for most language skills, and children who are strong in their L1 tend to learn L2 better with the same genetic effect. This common genetic effect may explain the cross-language transfer in phonological and morphological awareness and is probably the common learning mechanism that underlies cross-language transfer as argued in the interdependence hypothesis (Cummins 1979). In addition, especially the cross-language transfer in phonological awareness as well as the associations among phonological awareness, morphological awareness, and vocabulary in L2 may also be substantially explained by a common shared environmental foundation.

Practical implications and limitations

Our study underscores the importance of environmental influence on bilingual abilities. In particular, L2 vocabulary ability was strongly linked with SES and amount of L2 exposure. Perhaps L2 development depends very much on environmental input, and a rich environment for L2 learning matters a lot. Therefore, creating a L2-rich environment and exposing children to that environment could be an effective way to improve L2 abilities. For example, parents can encourage children to use L2 more often at home and provide children with videos and reading materials in L2. In addition, our study shows a common genetic effect for bilingual language skills. It suggests that children who have strong L1 abilities also tend to learn L2 well. On the other hand, children who have difficulty in developing in their L1 may encounter similar problems in learning L2, and this echoes previous findings (Chung and Ho 2010).

This study had some limitations. First, although English invented spelling used in this study reflects children's awareness of the phonological structure of English (e.g., Mann et al. 1987), it also involves printed letter recognition. Thus, our assertions about phonological awareness are limited by the fact that the phonological sensitivity measure administered in Chinese and English differed substantially. Although we felt that this was a necessary deviation given young Hong Kong Chinese children's unfamiliarity with phonemic skills in English, we acknowledge these differences in measures. Second, the amount of school English use was reported by parents and, hence, may not be entirely precise. In addition, the twin children in the same family might not use English exactly equally in frequency, although all the parents indicated that the twins' frequency of using English at home corresponded to the same scale on the questionnaire. Also, home and school English use were, respectively and retrospectively, measured via one item and, thus, the psychometric properties of the measure are uncertain. Finally, participants' age range was relatively wide. Although age was controlled for in the analyses, we cannot rule out the possibility that heritability estimates versus environmental effects might vary as a function of age. Therefore, future studies are needed to replicate the current findings.

Conclusion

This study shows a common genetic effect that may underlie the cross-language transfer in phonological and morphological awareness. This common genetic effect also explains the associations among bilingual phonological awareness, morphological awareness, and vocabulary. A common shared environmental effect may also substantially account for cross-language transfer in phonological awareness and the associations among L2 abilities. In addition, SES as well as home and school L2 use are important shared environmental influences on bilingual phonological awareness and L2 vocabulary. An L2-rich environment might be facilitative of the development of L2 vocabulary. Genetic influence seems to dominate to a larger extent in Chinese morphological awareness under favorable conditions. In addition, a larger amount of teaching in English is related to more individual differences in L2 English abilities caused by shared environment; this further implies the significance of environment in L2 learning.

Declarations

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Conflict of interest: Qiuzhi Xie, Mo Zheng, Connie S.-H. Ho, Catherine McBride, Fiona L.W. Fong, Simpson W. L. Wong, and Bonnie Wing-Yin Chow declare that they have no conflict of interest.

Ethical approval: This article does not contain any studies with animals performed by any of the authors. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Consent to participate: Informed consent was obtained from all individual participants included in the study.

Consent for publication: We consent to publish all parts of our manuscript, including tables and figures.

Availability of data and material: We included our database in our submission and consent that our data will be available to public.

Code availability: We used SPSS and OpenMx package in R to process and analyze data

Authors' contribution: Qiuzhi Xie conducted data analyses, wrote and revise the entire paper. Mo Zheng managed data collection and contributed to data analysis, result interpretation, and editing of the manuscript. Connie Ho and Catherine McBride supervised the project and revised the paper. Fiona Fong helped with data collection and drafted the section of Measures. Simpson Wong and Bonnie Chow contributed to the design of the overall project and suggested revisions on this paper.

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