A computer-based Pinyin intervention for disadvantaged children in China: Effects on Pinyin skills, phonological awareness, and character reading

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Abstract

Pinyin is an alphabetic script that denotes pronunciations of Chinese characters. Studies have shown that Pinyin instruction enhances both phonological awareness (e.g., Shu, Peng, & McBride-Chang, 2008) and character reading (e.g., Lin et al., 2010) in Chinese children. In the present study, we provided a three-week Pinyin intervention with a computer-based Pinyin GraphoGame to disadvantaged migrant children with poor Pinyin skills. A total of 252 first graders who were children of migrant workers in a large Chinese city were assessed to identify poor Pinyin readers. Fifty-six 7-year-old children with poor Pinyin skills were selected and randomly divided into a training group and a control group, with 28 children in each group. The training group played the Pinyin GraphoGame for three weeks while the control group received school instruction only during the same period. Results showed that the children in the training group outperformed their peers in the control group on Pinyin reading accuracy and fluency, onset-rime and phonemic awareness, and character reading. These results suggest that the Pinyin GraphoGame may be a cost-effective method to enhance Pinyin and literacy outcomes for underprivileged children in China.

Keywords*:* Pinyin, GraphoGame, computer-based intervention, low socioeconomic status, migrant children

Pinyin, an alphabetic script that denotes pronunciations of Chinese characters, is used in Mainland China to help children pronounce and recognize novel characters. Pinyin is typically introduced to children at the beginning of formal literacy instruction (Cheung & Ng, 2003). An increasing number of studies have shown that Pinyin instruction enhances both phonological awareness (e.g., Chen & Yuen, 1991; Cheung, Chen, Lai, Wong, & Hills, 2001; Shu et al., 2008; Xu & Ren, 2004; Ren, Xu, & Zhang, 2006) and character reading (e.g., Shu & Liu, 1994; Lin et al., 2010; Siok & Fletcher, 2001) in Chinese children. However, previous interventions on Pinyin focused primarily on typically developing children from middle-class families; little is known about disadvantaged populations, such as migrant children with poor Pinyin skills. To fill this gap, the present study examined whether a supplementary computerized Pinyin intervention enhances phonological awareness and character reading skills in migrant children who have poor Pinyin skills.

Pinyin Instruction, Phonological Awareness, and Character Reading

Chinese is a "morpho-syllabic" language in which each character corresponds to a syllable and a morpheme in the oral language. Accordingly, the pronunciation of each character (e.g., 妈, *mother*) can be represented by a Pinyin syllable (e.g., *mā*) comprised of an onset (e.g., *m*) and a rime (e.g., *a*). Each Pinyin syllable is also associated with a lexical tone. Chinese has a relatively simple syllable structure. Most Pinyin syllables have a CV structure; /*n*/ and /*ŋ*/ are the only two final consonants that can form CVC syllables (Siok & Fletcher, 2001). Pinyin consists of 21 onsets, 35 rimes, and 4 lexical tones (Institute of Linguistics, Chinese Academy of Social Sciences, 2004). The 26 letters in the Pinyin alphabet include virtually all of the corresponding letters from the English alphabet. The only letter unique to

the Pinyin script is *ü* /y/, while the letter *v* does not exist in Pinyin. Pinyin is a regular alphabetic system in that Pinyin letters correspond to the sounds they represent perfectly. About half of the onsets and rimes in Chinese are represented by letter combinations that comprise two to four letters. For example, the letter *s* can be used alone to represent /s/ or in combination with *h* to form the onset *sh* /ʂ/, and the letter *a* can represent */a/* or combine with *n* to form the rime *an /an/*. In this way, the 26 Pinyin letters are used to create 21 onsets and 35 rimes, which further combine into about 400 syllable segments in Mandarin Chinese (Wang, Anderson, Cheng, Park, & Thomson, 2008).

Tone is a suprasegmental feature in spoken Chinese that is always adhered to a rime unit (Wang, Perfetti, & Liu, 2003). Since Mandarin Chinese has four tones, the same syllable segment can represent up to four different pronunciations, depending on the tone it carries. For example, the syllables *mā* (妈, meaning "*mothe*r", high-level tone), *má* (麻, meaning "*hemp*", high-rising tone), *mǎ* (马, meaning "*horse*", falling-rising tone), and *mà* (骂, meaning "*curse*", high-falling tone) are pronounced differently and represent different morphemes because they carry different tones. There are about 1300 tone syllables in spoken Chinese (Wang et al., 2008). To master Pinyin, children need to acquire Pinyin letters and letter combinations and identify the tone of a Pinyin syllable.

Mastering Pinyin is a crucial component of Chinese literacy development in early school years (e.g., McBride-Chang, Liu, Wong, Wong, & Shu, 2012). Pinyin instruction has been utilized in primary schools in Mainland China for nearly five decades (Siok & Fletcher, 2001). Children typically receive intensive Pinyin training for ten weeks at the beginning of grade one (Wu, Li, & Anderson, 1999). They start with individual Pinyin letters and advance

to cluster onsets and rimes, before they finally acquire spelling rules of CV and CVC syllables. However, the typical ten-week Pinyin instruction may not be sufficient for children with poor reading skills, given that some children still experience difficulties in acquiring Pinyin skills at the end of the first grade (Li, Li, De, & Lyytinen, 2017). As such, supplementary Pinyin interventions can be beneficial to these children.

Textbooks and reading materials for young children typically have Pinyin notations. Pinyin enables children to pronounce unfamiliar characters and establish the print-to-sound correspondences for these characters independently (e.g., Shu, Zeng, & Chen., 1993; Shu & Liu, 1994). When children encounter a novel character, such as 虹 (*rainbow*), they can pronounce and recognize the character with the help of Pinyin (e.g., hóng). Since about 70-80% of the words in Chinese are compound words (Institute of Language Teaching and Research, 1986), children can easily figure out the meaning of a new character if they already know the other character in a compound word and the word is familiar in the oral language (Shu, et al., 1993; Shu & Liu, 1994; Wu et al., 2002). In the case of 虹(hóng, *rainbow*), for example, if they already recognize the character 彩 (cǎi, *colourful*), and know that 彩虹 (cǎi hóng, *colourful rainbow*) means *rainbow* in the oral language, they can recognize the character 虹 (hóng) independently by associating the pronunciation of the character with its orthographic form and meaning.

There is ample evidence that learning Pinyin enhances children's character reading (e.g., Siok & Fletcher 2001; Shu & Liu, 1994; Shu et al., 1993; Lin et al., 2010; Ding, Liu, McBride, & Zhang, 2015; Yin & McBride, 2018). For example, Siok and Fletcher (2001) found that children's pinyin knowledge at first grade significantly predicted their reading

abilities in grades 2, 3, and 5. Lin et al. (2010) showed that children's performance on an invented Pinyin spelling task was a unique predictor of word reading after controlling for phonological awareness. In the invented Pinyin spelling task, children heard five Pinyin syllables one at a time, and were asked to spell those syllables by organizing the Pinyin letters provided to them. The results suggest that children's early Pinyin representations are related to their later success in reading acquisition. Ding et al. (2015) confirmed Lin et al.'s (2010) findings and further showed that poor readers performed significantly worse on a similar invented Pinyin spelling task. Most recently, Yin and McBride (2018) demonstrated that even for kindergarteners who had not yet systemically acquired Pinyin, their levels of sensitivity to letter-sound correspondences in Pinyin syllables explained a significant amount of variance in word reading. The study also demonstrated that after acquiring Pinyin knowledge, first and second graders applied this knowledge to aid the learning of new characters. Taken together, the findings of these studies suggest that Pinyin skills have facilitative effects on character reading.

The positive effect of a Pinyin intervention goes beyond pronouncing characters correctly. Since Chinese is represented by a logographic script that consists of characters rather than letters, learning a transparent alphabetic system such as Pinyin enhances children's phonological awareness. A large number of studies have demonstrated that Pinyin instruction facilitates phonological awareness in Chinese children (e.g., Cheung et al., 2001; Cheung & Chen, 2004; McBride-Chang, Bialystok, Chong, & Li, 2004; Shu et al., 2008; Xu & Ren, 2004; Ren et al., 2006). Generally speaking, children with Pinyin skills outperform their peers without such skills on phonological awareness. In a study comparing first graders

in Mainland China and Hong Kong, McBride-Chang and colleagues (2004) observed that the former group performed better on both syllable and phoneme onset deletion tasks. This advantage was attributed to the Pinyin training in Mainland China since Hong Kong children learn to read characters without Pinyin. This facilitative effect was also reported by Shu et al. (2008), who found that Chinese children's performance on onset and tone detection tasks increased from chance (50%) to above 70% after receiving Pinyin instruction in grade one. Ren et al. (2006) compared the levels of phonological awareness between groups of kindergarten children with and without Pinyin instruction in Mainland China. The group that received Pinyin instruction scored higher than the control group on all the phonological awareness tasks, including syllable, onset, and rime detection tasks.

Using the Self-adaptive GraphoGame to Enhance Pinyin Learning

In recent years, computerized learning games have been increasingly used for educational interventions (e.g., Lyytinen, Ronimus, Alanko, Poikkeus, & Taanila, 2007). Compared to conventional instruction, computerized learning games have several distinctive advantages. They offer individualized opportunities for practice and provide immediate feedback and reinforcement. They are also fun, motivating, and cost-effective (e.g., Ronimus, Kujala, Tolvanen, & Lyytinen, 2014; Lyytinen et al., 2007). Extensive research has demonstrated that as a supplementary learning tool, computer-assisted training facilitates many aspects of literacy development such as phonological awareness (e.g., Chai, Ayres, & Vail, 2016), decoding (see Mahdi & Khateeb, 2019 for a meta-analysis) and vocabulary (see Chen, Tseng, & Hsiao, 2018 for a meta-analysis). According to Chen et al. (2018), the design of a game influences learning outcomes, regardless of a learner's age or linguistic

background. Games that maintain learners' motivation with proper levels of challenge are more engaging and lead to better outcomes than those that only emphasize drill and practice.

In the present study, we carried out a supplementary Pinyin intervention using the Pinyin GraphoGame. Our Pinyin GraphoGame adopted a learner-friendly self-adaptive algorithm, in that it calculates and maintains a reasonable level of difficulty to keep a learner motivated (e.g., Vilenius, Kujala, Richardson, Lyytinen, & Okamoto, 2007; Kujala, Richardson, & Lyytinen, 2010). The algorithm gathers information while the game is being played, and uses the data to profile a child's ability level in the game. This profile is then used to predict the child's learning outcome in a forthcoming learning trial (expected learning outcome) and estimate the probability of an incorrect response in the trial (expected motivational cost). The ratio between the outcome and the cost is optimized by adjusting the desirable difficulty level for each trial. When applied in a multiple-choice format, the algorithm estimates a learner's probability of success in identifying the correct answer from each of the distractors and uses this information to determine the number and the type of distractors. In other words, the GraphoGame adjusts the training content of subsequent trials based on the learning needs of each child and maximizes learning opportunities for the child (Vilenius et al., 2007; Kujala et al., 2010).

The original GraphoGame was developed at the University of Jyväskylä in Finland to provide systematic training on letter-sound correspondences in Finnish (see Richardson & Lyytinen, 2014, for a review). While the game was initially designed for children at risk for reading difficulties, it is now implemented across the entire country of Finland (Richardson & Lyytinen, 2014) and has been adapted into more than 20 alphabetic writing systems including

German (Huemer, Landerl, Aro, & Lyytinen, 2008), English (Kyle, Kujala, Richardson, Lyytinen, & Goswami, 2013), and several African languages (e.g., Ojanen et al., 2015). In addition, Chinese researchers have developed a Chinese Pinyin GraphoGame to provide Pinyin training for primary school students (Li et al., 2017; Li, Li, De, & Lyytinen, 2017; Yue et al., 2019).

To our knowledge, at least three studies have suggested that the Pinyin GraphoGame facilitates Pinyin skills for both typically developing children (Li et al., 2017) and poor Pinyin readers (Li, Li, De, & Lyytinen, 2017; Yue et al., 2019). Li et al. (2017) offered first graders a 4-week intervention with the Pinyin GraphoGame immediately after the participants completed Pinyin instruction at school. The children played the game on computers at home. The average training time was 153.77 minutes for the entire period, though the training time for each child varied due to the self-adaptive technology used in the game. After receiving the intervention, children in the training condition outperformed their peers in the control condition on both Pinyin reading accuracy and fluency. Moreover, the amount of play time was positively related to children's performance in the training group. In the second study, Li, Li, De, and Lyytinen (2017) provided an 8-week Pinyin intervention with the GraphoGame for first-grade children with poor Pinyin skills. Conducted at school in the second semester of grade 1, the training improved Pinyin reading accuracy for all participants. Children whose training time was longer than average made more gains in Pinyin reading accuracy and they also improved in Pinyin reading fluency. In the final study, Yue et al. (2019) provided an 8-week Pinyin GraphoGame intervention for 6-12 years old children with both reading disabilities and ADHD. Results showed that the intervention

improved the children's phonemic awareness and Pinyin recognition. Since all three interventions were conducted with children enrolled in public schools in Beijing, it is not clear whether the positive results can be generalized to other populations. The current study extended the investigation of Pinyin GraphoGame interventions to low-SES migrant children with poor Pinyin skills.

Education of Migrant Children in the City

Since China started the economic reform in 1978, an estimate of 150 million people has migrated from rural areas to cities to seek employment (Cui & Duan, 2006). Many migrant workers bring their children to the city. Unfortunately, despite the rapid economic growth in China, migrant families are typically low-income families. For example, the average income of migrant workers in Beijing, where the present study took place, is about one third of the average income of Beijing residents (Beijing Municipal Bureau of Statistics, 2018). Extensive research has demonstrated that SES affects language and literacy reading development (Huttenlocher, Vasilyeva, Waterfall, Vevea, & Hedges, 2007; González, 2001) and this is also true among Chinese children (e.g., Cheng & Wu, 2017; Zhang et al., 2013). The home language and literacy environment of families living in poverty is less stimulating, leading to worse outcomes in low SES children as compared to children of middle-class families.

In addition to low SES, children of migrant workers face other barriers in the Chinese education system. Non-resident children are prohibited from enrolling in public schools, as free education is only provided for resident children. The majority of children from migrant families are placed in private schools specifically established for non-resident populations.

These private schools charge tuitions but have far fewer resources than public schools (e.g., Wang, 2008; Goodburn, 2009). Located in abandoned buildings with poor ventilation and sanitation, these schools are in deplorable conditions (Han, 2001). They have neither a playground nor a library, some even miss restrooms, light fixtures, desks or chairs (Han, 2001). With respect to the curriculum, only two core courses, Chinese language arts and mathematics, are guaranteed. Other courses such as science, social studies, music, physical education, and English are often not offered due to a lack of adequate teaching expertise. Teachers who work at these schools are not certified. They also lack job security, and work longer hours with less pay (Lei, 2019). The class size in these private schools ranges from 45 to 70, which is much larger than the class size of public schools (around 30) (Han, 2001). The large class size prevents teachers from providing any individualized support to migrant children with special educational needs (Deng & Harris, 2008). At the same time, their low-income parents cannot afford private tutorial lessons outside of school. As such, migrant children with learning disabilities do not have access to special education services.

The Present Study

In the present study, we provided supplementary Pinyin training through the Pinyin GraphoGame to economically disadvantaged Chinese migrant children who had difficulties in acquiring Pinyin skills. All three previous studies (Li et al., 2017; Li, Li, De, & Lyytinen, 2017; and Yue et al., 2019) were conducted with children enrolled in public schools in Beijing. These children were residents of the city and they came from middle- to high-income families. They played the Pinyin GraphoGame on PC computers at home, and their playtime was monitored by teachers, parents, or researchers, who then encouraged them to

spend more time on the game. By contrast, the present study was implemented in private schools for migrant children. The Pinyin GraphoGame was offered by PC tablets in the mobile library set up by the researchers at their schools. Since these migrant children did not have many resources either at school or at home, the mobile library afforded them an opportunity to access electronic devices. Due to these differences, the effectiveness of the Pinyin GraphoGame in improving Pinyin skills needs to be examined among children from disadvantaged backgrounds. Moreover, the previous studies demonstrated that the Pinyin GraphoGame improved Pinyin skills, but they did not examine whether similar facilitative effects could be found on literacy outcomes. Thus, the current study also aimed to investigate whether Pinyin GraphoGame facilitates migrant children's phonological awareness and character reading.

The participants of the present study were low-SES migrant children whose Pinyin skills significantly lagged behind their peers in the second semester of Grade 1, half a year after they completed the formal Pinyin instruction at school. We targeted this population for two reasons. First, given that SES is a significant predictor of Chinese children's phonological skills (e.g., Zhang et al., 2013), children from low-SES families likely face more challenges in literacy development. Second, the individualized learning needs of migrant children are not met by the Chinese school system (e.g., Wang, 2008; Goodburn, 2009). Under these circumstances, the Pinyin GraphoGame may be a useful intervention tool because it involves relatively few resources, is adapted to the level of each child, and is user-friendly. Inspired by the positive effects of adaptive game interventions on low-SES populations reported in previous research (e.g., Wilson, Dehaene, Dubois, & Fayol, 2009;

Rosas, Escobar, Ramírez, Meneses, & Guajardo, 2017), we designed an Android version of the Pinyin GraphoGame for this study.

The participants were randomly divided into a training group and a control group, and both groups were tested on Pinyin reading accuracy and fluency, syllable awareness, onset-rime and phonemic awareness, and character reading before and after the intervention. We proposed three hypotheses. First, we expected the Pinyin GraphoGame intervention to improve the Pinyin skills of low-SES Chinese children who still have poor Pinyin reading skills after they complete the school instruction. Second, it was hypothesized that the intervention would facilitate children's phonological awareness. Considering that syllable awareness develops before onset-rime and phonemic awareness and is less challenging to children with reading difficulties (e.g., Shu et al., 2008; McBride-Chang et al., 2012), it is possible that the Pinyin GraphoGame intervention would lead to greater gains in the measure assessing onset-rime and phonemic awareness than the measure assessing syllable awareness. Finally, we hypothesized that the intervention would lead to better character reading skills.

Method

Participants

To identify poor Pinyin readers, we recruited 252 first graders (mean age 7 years and 1 month, 139 boys and 113 girls) from two private schools in Beijing, China. The participants were disadvantaged children from migrant families. At the beginning of the study, they were in the second semester of the first grade and had received formal Chinese reading instruction for six months using Pinyin as a scaffold. To identify poor Pinyin readers, all children were assessed using a Pinyin reading accuracy task that targeted Pinyin decoding and

comprehension. Children were presented with a word or a sentence written with Pinyin followed by four pictures, and they were asked to choose the picture that depicted the meaning of the item. The task had a total of 40 items. If a student performed below 30% percentile of all the students in his/her own school and was confirmed by his/her teacher as facing difficulties in mastering Pinyin skills, the student was identified as a poor Pinyin reader. We used a Pinyin reading task for identification because Chinese first graders only know a small number of characters and cannot read without Pinyin. Fifty-six children (mean age 7 years and 2 months, 28 boys) met this screening criterion. They were randomly divided into an intervention group and a control group, with 28 children in each group.

Measures

A battery of measures including Pinyin reading fluency, Pinyin reading accuracy, syllable awareness, phonemic awareness, and Chinese character recognition was administrated to both the intervention group and the control group before and after the intervention. All of the measures were administered individually in the aforementioned order by trained research assistants who were university students majoring in psychology.

Pinyin reading accuracy Children were asked to read 50 real syllables and 20 pseudo-syllables arranged in order of increasing difficulty. Testing was stopped when children failed to recognize ten consecutive Pinyin syllables. One point was given when an item was pronounced correctly, with a maximal score of 70. The test-retest reliability was $r = .858$ (The test-retest reliabilities reported in the current study were all calculated on the control group).

Pinyin reading fluency Children were instructed to read aloud the Pinyin syllables in this task one by one as fast and accurately as possible within two minutes. This task contained 100 highly frequent syllables presented in a randomized order. A syllable was scored as correct only when the onset, rime and tone were all read correctly. The score was calculated as the number of syllables read correctly per minute. The test-retest reliability in the present study was r = .930.

Syllable deletion Adapted from Li, Shu, McBride-Chang, Liu, and Peng (2012), this task consisted of ten items with four two-syllable items and six three-syllable items. Half of the items were real words in spoken Chinese, whereas the other half were nonwords. Each item was orally presented by the experimenter, and children were asked to remove a syllable in the initial, medial, or final position. For example, children were asked to remove /nā / from /nā kú/. The task had three practice items. One point was given for each correct item, with a maximal score of 10. The test-retest reliability was r = .705.

Rime and phoneme deletion Adapted from Li et al. (2012), this measure was designed to reflect the phonological features of Chinese syllables. The task consisted of 12 single syllables. Four of the items required children to delete the initial phoneme from a syllable. For example, say /gài /, now say /gài/ without /g/. The answer was /ài/. Since Chinese does not have onset clusters, the initial phoneme is also the onset of a syllable. Four of the items required children to remove the rime from a syllable. For example, say /mèi/, now say /mèi/ without /èi/. The correct answer was /m/. Four of the items asked children to remove the medial phoneme from a syllable with a diphthong. For example, say /shuǎng/, now say /shuǎng/ without /u/. The correct answer was /shǎng/. The task contained three practice items.

One point was given for each correct response, and the maximal score was 12. The test-retest reliability was $r = .604$.

Character recognition The character reading task reported in Li et al. (2012) was used in the present study. The task consisted of 150 single characters that covered a range of difficulty levels. Children were asked to read from the beginning of the list and testing was stopped when they failed to read 15 consecutive items correctly. This task had a test-retest reliability of $r = .901$.

Intervention The intervention was conducted through a digital Pinyin GraphoGame installed on a tablet PC. The Pinyin GraphoGame consisted of four phases, a presentation phase, a practice phase, a feedback phase and a reward phase. The phases are displayed in Appendix A. As shown in Part A of the appendix, when children enter the Pinyin GraphoGame, they can either clink on the Pinyin book icon on the right to start playing the game, or they can click on the picture book icon on the left to review their individualized picture book (see more details about the picture book in the reward phase below). The Pinyin GraphoGame contained a total of 15 streams presented in an order of increasing complexity. Across different streams, children first learned basic units of Pinyin including single Pinyin letters, rimes, and tones, and then learned how to decode Pinyin syllables with these units. Each stream was further divided into 6-15 levels, with 3-8 Pinyin items in each level. As an example, Stream 1 and Stream 9 of the game are displayed in Appendix B. The materials were organized based on the pinyin list in the first volume of the Elementary School Textbooks in Mainland China (Elementary Education Teaching and Research Center, Beijing Education and Science Institute, 2011). Prepared by the Ministry of Education, the textbooks

were used in Beijing and several other regions.

In the presentation phase (Part B of Appendix A), children were asked to map the Pinyin units they heard via headphones to the written forms of these units they saw on the screen. A brief introduction was given at the beginning of each level before children were exposed to any Pinyin items. For example, in Stream 1, children were told that they were about to learn three Pinyin letters, *a, o,* and *e*, and were asked to listen to the sounds and look at the letters on the screen carefully. Once the stream formally began, one sound was orally presented (e.g., /*a*/), and the corresponding Pinyin unit was shown on the screen at the same time (e.g., *a*). The sound was repeated three times, each time accompanied by a flash animation of the Pinyin unit. This allowed children to build a connection between the sound and the Pinyin unit. In subsequent levels of Stream 1, children were exposed to the same Pinyin letters combined with each of the four tones. The Pinyin items became increasingly complex across streams, but the basic Pinyin letters were always presented together with rime units to reinforce learning. For example, in Stream 9 Level 1, children were presented with five items, *a*, *i*, *e*, *ai*, and *ei*. Three items (*a*, *i*, *e*) have appeared before and two items (*ai* and *ei*) were novel. This stream consisted of 15 levels. Across the levels, children first learned each Pinyin unit combined with different tones, e.g., /*āi*/ and /*ěi*/, and then full syllables containing these units, e.g., /*dài*/ and /*pèi*/, again in an order of increading complexity.

Within each stream, after children completed the presentation phase of a level, they moved to the practice phase for this level (Part C of Appendix A). In the practice phase, children were tested on the Pinyin items they just learned and provided with corrective feedback. In a test item, children heard a sound and were asked to choose the Pinyin unit that

corresponded to the sound from 2 to 8 distractors shown on the screen. Using the self-adaptive technology, this phase started with trials with a small number of distractors (i.e., 2-3) and the number of distractors increased (e.g., 4-8) as the phase continued. Children's accuracy data was collected by the software and the level of difficulty of the subsequent trials was adjusted based on the performance on earlier trials. For example, if a child had difficulty in distinguishing *ā* from *á*, but was able to differentiate *ā* from *ě*, *á* would be a more difficult distractor for *ā* than *ě*. The number of trials for each level was roughly three times of the number of items children were exposed to in the presentation phase. After children completed all the trials in the practice phase, they moved to the feedback (Part D of Appendix A) and reward (Part E of Appendix A) phases associated with this level.

The feedback and reward phases were designed to motivate children to play the game. After children completed the trials in the practice phase, an overall accuracy rate appeared in the feedback phase. On the same screen, children were provided with several digital stickers to choose from. The number of stickers was positively related to the accurate rate of the practice phase--a child who performed well was offered a larger selection of stickers. After a sticker was chosen, children moved to the reward phase, in which they placed the sticker in their individualized picture books. At the beginning of the Pinyin GraphoGame, the picture book only had templates (e.g., an empty garden). Children added stickers to each template as they were earned throughout the game. If children reached the criterion of 80% accuracy in the practice phase associated with a level, they moved on to the next level of the same stream after completing the feedback and reward phases for the current level. They would go through the same four phases with the new level. If they did not reach the criterion in the

practice phase for the current level, they would still complete the feedback and reward phases but then go back to the same level afterwards.

After the pre-test, the Pinyin GraphoGame intervention was given to the training group in 5-10-minute sessions 2-3 times daily during school hours for three weeks. The children in the training group were engaged in the Pinyin GraphoGame with PC tablets in the mobile library under the supervision of two research assistants. The researchers encouraged the training group to play the game as many times as possible when they visited the mobile library by awarding them with small gifts, such as pencils or notebooks. The total training time of the intervention group ranged from 231 to 517 minutes (M = 378.46, SD = 80.38), and they achieved 3 to 15 streams by the end of the three-week period, with a mean of 11.57 streams (SD = 3.73). The variation among children in terms of the training time and game progress was due to the nature of the self-adaptive technology adopted by the Pinyin GraphoGame. While the training group received the intervention, children in the control group listened to music, attended physical education classes, read books in the mobile library or played on the playground after lunch.

Results

Table 1 displays the means and standard deviations for each group on each of the five tasks before and after the intervention with the Pinyin GraphoGame. There was no significant difference in any of the five tasks between the training group and the control group before the intervention, $ps > .05$. To assess the effect of the Pinyin GraphoGame in promoting children's Pinyin and reading skills, we analyzed the data of each task with a 2 (group: intervention vs. control) × 2 (time: pre- vs. post-test) mixed-design ANOVA. For these analyses, group was a

between-participant factor and time was a within-participant factor.

For the Pinyin reading fluency task, we observed a significant time effect favoring the post-test and a significant time-by-group interaction, F (1, 54) = 7.78, $p < .01$, $\eta_p^2 = .126$, F (1, 54) = 8.52, $p < .01$, $\eta_p^2 = .136$, respectively. A simple effect analysis indicated that the two groups were comparable at the pre-test, F (1, 54) = .01, $p = .927$, but the training group performed significantly better than the control group at the post-test, F (1, 54) = 16.29, $p < .001$, $\eta_p^2 = .232$. Similarly, for the Pinyin reading accuracy task, the results showed a significant main effect of time favoring the post-test, F (1, 54) = 4.76, $p < .05$, $\eta_p^2 = .081$. The interaction between group and time was also significant, F (1, 54) = 6.72, $p < .05$, $\eta_p^2 = .111$, in that the two groups were comparable at the pre-test, F (1, 54) = .09, $p = .772$, $\eta_p^2 = .002$, but the training group was significantly better than the control group at the post-test, F (1, 54) = 11.39, $p < .001$, $\eta_p^2 = .174$. These results suggest that the Pinyin GraphoGame intervention supports children's development of Pinyin reading accuracy and fluency.

For the rime and phoneme deletion task, we observed a significant main effect of time favoring the post-test, F (1, 54) = 8.18, $p < .05$, $\eta_p^2 = .131$. There was also a significant main effect of group, with the training group outperforming the control group, F (1, 54) = 4.59, $p < .05$, $\eta_p^2 = .078$. Importantly, the interaction was significant, F (1, 54) = 6.23, $p < .05$, $\eta_p^2 = .103$. While the two groups were comparable at the pre-test, F (1, 54) = .07, $p = .798$, $\eta_p^2 = .001$, the training group scored higher than the control group at the post-test, F (1, 54) = 14.34, $p < .001$, $\eta_p^2 = .210$. Notably, a somewhat different pattern was found in the syllable deletion task. While the main effect of time was significant favoring the post-test, F (1, 54) = 8.18, $p < .01$, $\eta_p^2 = .132$, no significant group or interaction effects were found, F (1, 54)

= .05, p = .821, η_p^2 = .001, and F (1, 54) = .004, p = .947, η_p^2 = .000, respectively. These results indicate that the Pinyin training accelerates children's phonological awareness only at the onset-rime and phonemic levels, but not at the syllable level.

For the Chinese recognition task, neither the main effect of time nor that of group was significant, F (1, 54) = 3.83, p = .06, η_p^2 = .067, F (1, 54) = 1.12, p = .295, η_p^2 = .021, respectively. However, the interaction was significant, F (1, 54) = 4.09, p < .05, η_p^2 = .072. There was no difference between the two groups at the pre-test, F (1, 54) = .002, p = .964, η_p^2 = .000, but the training group became significantly better than the control group at the post-test, F (1, 54) = 8.06, p < .01, η_p^2 = .132. Thus, the Pinyin GraphoGame significantly improved Chinese reading for children in the training condition.

Discussion

The present study was conducted to evaluate the effectiveness of the Pinyin GraphoGame in improving Pinyin skills, phonological awareness, and character reading for first graders who were children of migrant workers and had poor Pinyin skills. The intervention was provided within a three-week interval. In support of our three key hypotheses, the Pinyin GraphoGame produced significant gains in Pinyin skills, phonological awareness, and character reading in the training group. These results are not only consistent with previous studies on the Pinyin GraphoGame in terms of Pinyin skills (Li et al., 2017; Li, Li, De, & Lyytinen, 2017; Yue et al., 2019) and phonological awareness (Yue et al., 2019), they also extend the benefits of the game to character reading. Importantly, we demonstrate that as a supplementary training tool, the Pinyin GraphoGame facilitates the literacy development of economically disadvantaged children with learning challenges.

The Effects of the Pinyin GraphoGame on Pinyin Skills, Phonological Awareness, and Character Reading

In line with Li et al.'s (2017) findings with typically developing children from middle-class families, we found that Pinyin GraphoGame improved both Pinyin reading accuracy and fluency in migrant children from low SES backgrounds. However, our findings with respect to Pinyin skills are somewhat different from those of Li, Li, De, and Lyytinen (2017), who found that the Pinyin GraphoGame improved Pinyin reading accuracy but not fluency for poor Pinyin readers. It is worth noting that in Li, Li, De, and Lyytinen (2017), children whose training time was above average (M = 93.37 minutes) also improved significantly in fluency. In the present study, our participants' training time ranged from 231 to 517 minutes, far beyond that in Li, Li, De, and Lyytinen (2017). Thus, it seems that the training effect is positively related to the amount of time children spend playing the game.

The current results also suggest that Pinyin training improves children's phonological awareness. Interestingly, our participants demonstrated gains only at the onset-rime and phonemic levels, but not at the syllable level. These findings are consistent with those of Shu et al. (2008) and Yue et al.(2019), but they are somewhat different from several studies that also reported gains in syllable awareness (e.g., McBride-Chang et al., 2004; Ren et al., 2006; Li et al., 2017). This inconsistency is likely due to the different learning stages of the participants across the studies. Both McBride-Chang et al. (2004) and Ren et al. (2006) included kindergarteners in their samples, and Li et al. (2017) included children in the first semester of grade one who were receiving Pinyin instruction at school during the study. By contrast, the current study was conducted on older children in the second semester of first

grade, who had completed their Pinyin training at school. Our participants also had more experience learning Chinese characters with the help of Pinyin. Because syllable awareness develops earlier than onset-rime and phonemic awareness (e.g., Shu et al., 2008), children in the present study already reached a relatively high level of syllable awareness (71%) before the intervention. Furthermore, the Pinyin GraphoGame was designed to focus on monosyllabic words. Children learned to spell Pinyin syllables using learned Pinyin letters and units, which only required phonological awareness at the onset-rime and phonemic levels (Lin et al., 2010). The game did not offer any training on syllable awareness. Thus, the Pinyin GraphoGame had a more pronounced effect on phonemic awareness than syllable awareness.

In keeping with findings reported in previous studies, the Pinyin GraphoGame also improved children's character reading in our study (e.g., Lin et al., 2010; Ding et al., 2014; Yin & McBride, 2018). Importantly, low-SES children with poor Pinyin skills were able to experience significant improvement in character recognition within a short three-week intervention. We offer two explanations for the gains. First, as children improve their Pinyin skills, they utilize these skills to learn new characters both in Chinese language classes at school and through daily reading outside of school. Textbooks and reading materials in the early grades typically have Pinyin notations. As such, Pinyin skills help children recognize and pronounce unfamiliar characters and enable them to establish print-to-sound correspondences independently (e.g., Shu et al., 1993; Shu & Liu, 1994). Previous studies have shown that poor readers were able to achieve better comprehension of passages with Pinyin notations, compared to similar passages without Pinyin (e.g., Li, Wu, Zhang, Zheng, & Zhu, 2011; Wu, Zhang, Shu, Li, Anderson, & Li, 2002). Taken together, our research

demonstrates that poor Pinyin readers are capable of reading novel characters via Pinyin, and an intervention on Pinyin skills enhances their character reading.

Second, the Pinyin GraphoGame may also improve children's character learning through phonological awareness. Although Chinese is not an alphabetic language, many studies have shown that phonological awareness predicts unique variance in character recognition among Chinese children (e.g., McBride-Chang & Ho, 2000; Shu et al., 2008). According to the universal phonological principle, reading of any written language involves activating phonology (Perfetti, Zhang, & Berent, 1992). In addition, different aspects of phonological awareness may facilitate character reading in different ways. Syllable awareness is essential for identifying characters because each character in print corresponds to a syllable in the oral language. About 72% of Chinese characters are compound characters with a phonetic radical (Shu, Chen, Anderson, Wu, & Xuan, 2003). Many characters are semi-regular, which means a character (e.g., 虹, hóng) and its phonetic radical (e.g., 工 gōng) do not have the same pronunciation but are related phonologically. In these cases, onset-rime and tone awareness may help children derive and remember the pronunciation of the character from its phonetic, with the support of context (Cheung, 2003). Finally, literacy practices affect how characters are read (Shu et al., 2008). In Mainland China where the present study took place, a character is pronounced as a combination of an onset and a rime in Chinese language classes as well as in dictionaries. However, due to our small sample size, we were not able to explore the mediation effect of phonological awareness on the relationship between Pinyin skills and character reading. Future research is needed to clarify the nature of this relationship.

Helping Disadvantaged Children with Educational Computer Games

While previous studies offering similar interventions involved middle-class children with typical (Li et al., 2017) or poor (Li, Li, De, & Lyytinen, 2017; Yue et al., 2019) Pinyin skills, our study extends the effectiveness of the Pinyin GraphoGame to low-SES migrant children with poor Pinyin skills. Our results demonstrate that the Pinyin GraphoGame is an effective learning tool for migrant children by providing supplementary instruction in mobile libraries set up at their schools. Because the Pinyin GraphoGame is cost-effective and does not require extensive training, it can be used under less than optimal but ecologically realistic learning conditions. While the children in the present study were monitored by research assistants, due to the undemanding nature of the game, we believe that teachers or volunteers can be easily trained to provide the same support.

We attribute the promising results observed in the present study to the individualized learning opportunities provided by the learner-friendly self-adaptive algorithm in the Pinyin GraphoGame, the effectiveness of which has been reported in both computer simulation (e.g., Kujala et al., 2010) and empirical studies (e.g., Richardson & Lyytinen, 2014). This self-adaptive algorithm is superior to previous self-adaptive algorithms in that it maintains learners' motivation by adjusting the content of subsequent trials based on the learning progress of each child. The motivation factor, combined with the adverse learning conditions faced by migrant children, may explain the difference in the average training time reported between the present study (378.46 minutes) and Li, Li, De, and Lyytinen (2017) (182.89 minutes). Children from middle-class families are used to playing computer games and thus are not particularly interested in exploring learning games. By contrast, low SES migrant

children are more willing to engage in computer learning games such as the Pinyin GraphoGame due to their limited access to resources. Under these circumstances, providing them with the Pinyin GraphoGame on computer tablets may be a quick and cost-effective way to improve their Pinyin and reading skills, and to compensate for their lack of resources at home and school.

Our findings have significant implications for elementary education for about 160 million children in rural China (Zhao, Zhou, Wang, Jiang, & Hesketh, 2017). The quality of schools varies widely in China; students who reside in rural areas have far fewer educational opportunities than those who reside in cities (Brock, 2009). Given that children who reside in rural areas face many of the same challenges as migrant children, the positive results observed in the current study point to the possibility that a computerized, self-adaptive intervention may be useful for low SES children with learning challenges across different regions in China. However, due to the vast economic gap and the digital divide between urban and rural areas in China, low-SES children in the countryside have even less experience with digital devices such as computers, cell phones or tablets (e.g., Yang et al., 2013) than migrant children in the city. Their lack of digital experience, combined with poor living and learning conditions, present obstacles to Pinyin GraphoGame interventions. Future studies should explore whether the Pinyin GraphoGame can be successfully implemented with children who reside in rural China, as applying these games may reduce the achievement gap between low- and high-SES children.

Limitations, Future Directions, and Conclusion

Several limitations should be considered in the interpretation of our results. First,

since our participants were migrant children with poor Pinyin skills, our findings may not be directly applicable to other populations, such as low-SES children in rural China. Future research is needed to examine the effectiveness of the Pinyin GraphoGame in other low-SES populations. Second, due to time constraints, not all the participants in the training group completed the game by the end of the three-week intervention. The intervention effects might have been more robust if all children had finished the game. Future studies should consider implementing the Pinyin GraphoGame within a longer time frame. A more extended study would also allow researchers to observe whether the effects of an intervention can be sustained over time. Finally, it is noteworthy that the self-adaptive algorithm used in the Pinyin GraphoGame is domain general (Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009). Reading intervention is just one example of application among many possibilities. Future studies should explore the use of self-adaptive computer-based learning games in other domains, such as mathematics.

In conclusion, the present study suggests that computer-assisted Pinyin training facilitates low-SES migrant children's Pinyin skills, onset-rime and phonemic awareness and character reading. Since low-SES children with learning challenges do not receive special education supports in China, providing supplementary interventions with educational computer games may be an effective solution to reduce the achievement gap between these children and their higher-SES peers.

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Table 1

Variable means and standard deviations in two groups before and after the intervention.

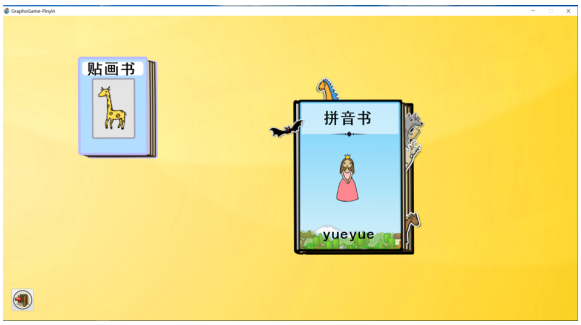
Variable		Training* (*n*=28)			Control (*n*=28)		
		Pre-test	Post-test	Gain	Pre-test	Post-test	Gain
Boys/Girls		17/11			18/10		
Age in months		85.50 (4.88)			87.00 (5.96)		
Pinyin reading	Accuracy [a]	17.71 (19.47)	23.93(18.27)	6.21(8.77)	16.64(20.53)	16.11(18.79)	.54(10.63)
	Fluency [b]	5.96 (5.45)	8.32 (8.31)	2.36 (3.83)	5.52 (5.69)	5.46 (5.09)	-.05 (2.10)
Phonological awareness	Syllable [a]	7.14 (2.69)	7.93 (2.46)	.79 (2.40)	7.04 (2.12)	7.79 (1.79)	.75 (1.53)
	Phonemic [a]	5.25 (3.63)	7.36 (3.31)	2.11 (3.08)	4.54 (3.00)	4.68 (3.27)	.14 (2.80)
Character recognition		13.89 (11.48)	16.14 (12.15)	2.25 (4.65)	12.19 (8.33)	12.15 (11.07)	-.04 (3.66)

[a] number of correct responses. Numbers in parentheses represent the standard deviation.

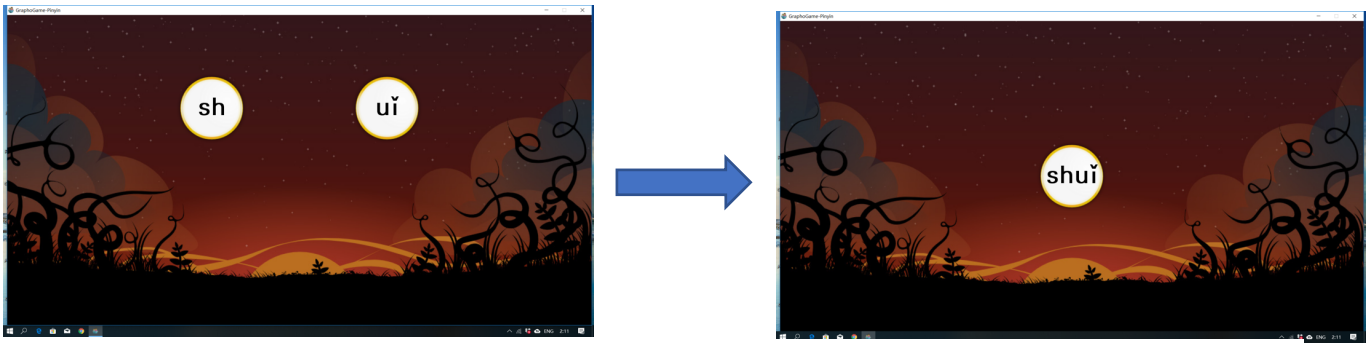
[b] number of correct responses per minutes (limited in 2 min).

* For the training group, training time ranges from 231 to 517 min, *M*=378.46 *SD*= 80.38, training level ranges from 3 to 15 streams, *M*=11.57 *SD*= 3.73.

Appendix A: A Flowchart of the Pinyin GraphoGame.

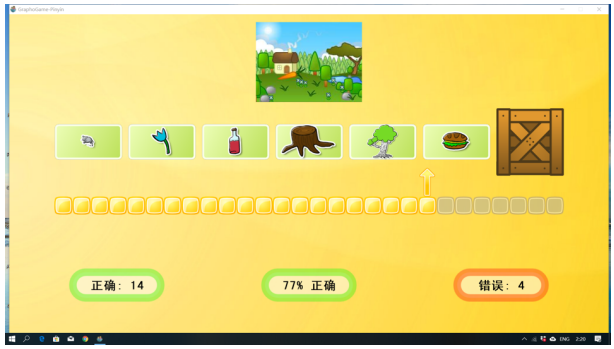


Part A: Game interface (left: picture book; right: Pinyin book)

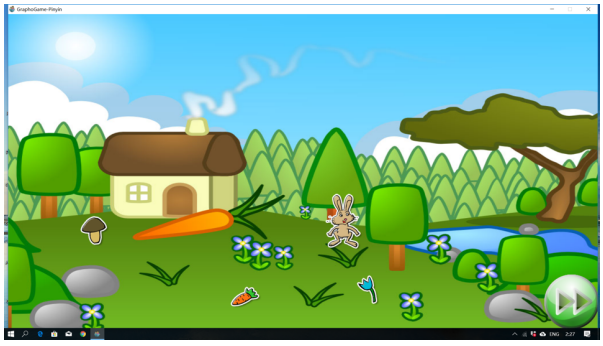


Part B: Presentation phase (left: the animation of spelling the syllable shuǐ; right: the syllable shuǐ)

Part C: Practice phase



Part D: Feedback phase (correct responses: 14; accuracy rate: 77%; incorrect responses: 4)



Part E: Reward phase

Appendix B: Same items in the Pinyin GraphoGame.

Stream	Level	Pinyin Item							
stream_01	level_01	a	o	e					
stream_01	level_02	ā	á	ǎ	à				
stream_01	level_03	ō	ó	ǒ	ò				
stream_01	level_04	ē	é	ě	è				
stream_01	level_05	ā	á	ě	è	ō	ǒ		
stream_01	level_06	ǎ	à	ē	é	ó	ò		
stream_09	level_01	a	i	e	ai	ei			
stream_09	level_02	āi	ái	ǎi	ài	ēi	éi	ěi	èi
stream_09	level_03	ei	u	i	ui				
stream_09	level_04	ēi	éi	ěi	èi	uī	uí	uǐ	uì
stream_09	level_05	dài	tái	nǎi	lái	bǎi	zài		
stream_09	level_06	shǎi	shuǎi	hài	huài	gāi	guāi	zhuài	zhài
stream_09	level_07	bèi	péi	mèi	fēi	wěi	léi		
stream_09	level_08	zhuī	chuí	shuǐ	ruì	zuǐ	tuī		
stream_09	level_09	gǎi	gěi	guǐ	cài	cèi	cuì		
stream_09	level_10	pài	hài	nèi	lèi	wèi	suì		
stream_09	level_11	cái	sài	zéi	lěi	huǐ	kuī	wài	
stream_09	level_12	mài	mèi	mì	mà	mò	mù		
stream_09	level_13	cuī	cū	cuō	chuī	chū	chuō	cāi	
stream_09	level_14	zhài	zhà	zhuī	zhú	zhuō	zhuā	zhě	
stream_09	level_15	gǎi	gěi	guǐ	cài	cèi	cuì		