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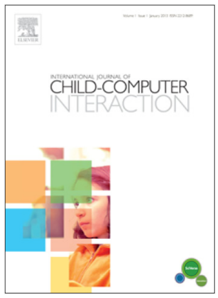

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A Design Case Study of a Tangible System Supporting Young English Language Learners

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Abstract

Many researchers have suggested that tangible user interfaces (TUIs) have the potential to support learning for children. While several tangible reading systems have been developed for children, few systems have been designed that explicitly target the first stage of reading where many children struggle, which is the alphabetic principle (letter-sound correspondences). We present a tangible reading system called PhonoBlocks that supports children learning English letter-sound correspondences. PhonoBlocks uses 3D tangible letters that change colour to draw attention to the moment that adding other letters changes the sounds. We then present a mixed-methods case study with ten Mandarin-speaking children in China using our system. Results showed that the Chinese children achieved significant learning gains relative to their baseline performance after PhonoBlocks instruction. The results also point to design features of our system that enabled behaviours that are correlated with learning. We compare the results of this study to a different study with eight at-risk monolingual English-speaking children in Canada using PhonoBlocks in learning to read and spell. By comparing results, we generalize and make three recommendations for designing tangible reading systems for all children who must learn the alphabetic principle. We also discuss three recommendations that are specifically for children learning English as a foreign language.

Keywords:

Tangible user interfaces (TUIs); English as a Foreign language (EFL); dyslexia; children; reading acquisition; mixed-methods.

1. Introduction

English has become an international language widely used by people all over the world. There is a growing number of young English language learners (ELLs). Every year, English-speaking countries, such as Canada and the U.S., receive a large number of immigrants; immigrant children from non-English speaking countries have to learn English, the language of the main

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culture, at school. Language training programs can also be seen in non-English-speaking countries like China, Japan, and Korea, wherein the children learn English as a foreign language (EFL). Many ELL and EFL children struggle with learning English because it is not their first language and the children may lack adequate resources to support their learning [43,48,50]. Learning to read and spell English is also challenging for many monolingual English-speaking children. Approximately 10% of children in English-speaking countries are reported to have difficulties in learning to read (which is also referred to as “dyslexia”) [33]

Successful early reading acquisition of English requires children to (1) learn phonological awareness (PA), the ability to manipulate speech sounds, and (2) understand the alphabetic principle, a set of rules that explain how letters (graphemes) are associated with sounds (phonemes) [8,41]. Research shows that PA and the alphabetic principle are reciprocal so that poor PA could lead to further difficulty in learning the alphabetic principle, and vice versa [25]. For example, monolingual English-speaking children at-risk for dyslexia are suggested to have phonological deficits, which impedes the children to acquire the alphabetic principle and word reading ability [41]. Besides, the "opaque" orthography of English poses particular challenges for some children [8]. An orthography is a system that represents how letters are linked to sounds in a language [3]. In English, letter-sound correspondences are not entirely consistent (e.g. the sound of /a/ in *b**a**d*, *g**a**me*, *st**a**r*; /k/ may be spelled with *c* or *k*), which may increase some children’s difficulty in learning the alphabetic principle [36,51].

Researchers have agreed that EFL children learn to read and spell English in generally similar ways as monolingual English-speaking children [6,13,47]. Specifically, for both groups of children, performance on PA is a strong predictor of their future success or failure in the acquisition of the alphabetic principle and subsequent reading abilities [13,47], and learning the alphabetic principle can contribute to children's PA [41,47]. However, most researchers have agreed that learning to read English as a foreign language is more complicated than learning to read English as a language of cultural origin [32,48]. Such a learning process could be even more complex for EFL children whose first language is non-alphabetic, such as Chinese [32,43,46]. For example, many Chinese students are reported to have poor PA and limited knowledge of the alphabetic principle [46].

Three main reasons may account for Chinese students' poor PA. First, Chinese language acquisition (the first language) has a transfer effect on English language acquisition (a foreign language), and vice versa. and the transfer impact can be large when the orthographies of two languages differ too much [43,46]. Learning to read and spell the English alphabet requires children to learn letter-sound correspondences while learning to read and spell the morphosyllabic Chinese language requires children to learn both the morphemes associated with the semantic radical as well as the spoken syllables associated with the phonetic radical (if there is one) [8,24]. That is, the learning of English calls for more “fine-grained” phonological analysis than that in learning Chinese. Second, a learner’s PA ability can be influenced by literacy instruction [5,47]. Most studies on primary school English language teaching in China have indicated that the quality of primary school teachers is poor [16,23,44]. This problem is even worse in cities and towns that have less economic diversity [16,44]. Third, compared to native English speakers, EFL children are less proficient in using the English spoken language system or lack language background knowledge and, therefore, may not be familiar with the sounds that map to letters [40].

Because both EFL children and at-risk children have similar problems with PA, their reading problem might be addressed using the same method. Traditional multisensory phonics-based instructions are often used to help EFL children [12,17,35] and at-risk children [19,29,42]. This approach uses linked visual, auditory, tactile, and kinaesthetic senses to attract children's attention and explicitly teach them the alphabetic principle [19]. One well-known multisensory program used for preschool children is the Montessori program method [22,34]. The Montessori method emphasizes the importance of children's hands-on learning with multisensory materials in supporting their general cognitive development. For example, children are first taught to trace wooden plane geometric forms, and then trace sandpaper letters with their fingers when learning to read letters [34]. The Orton-Gillingham (O-G) program, which specifically focuses on language interventions for at-risk children, was then developed based on the Montessori method and other multisensory methods [42]. In addition to the multisensory aspect, O-G programs highlight the importance of structured, sequential, and phonics-based contents as well as over-learning [19]. Physical letter tiles or coloured beads are often used in the O-G program to facilitate the letter tracing and letter manipulating activities. However, these programs do not involve computational materials and rely on highly trained teachers who provide many one-to-one sessions with structured guidance and feedback.

Recent research has suggested the potential of tangible user interfaces (TUIs) in supporting learning to read for children [1,10,15]. TUIs share several advantages commonly associated with computers, such as: cost-effectiveness [10,28]; digital feedback; playful learning through multimedia (e.g. text, images, sounds, and objects); and motivational game-mechanisms [26]. Compared to graphic user interfaces (GUIs) (e.g. Dybuster [18], Fast ForWord®[27]), tangible letters make it easy for children to position, organize, or trace the letters while hearing associated sound changes; because computation can be embedded in these tangible letters, they can also change their colour to draw children's attention [39]. There are several tangible reading prototypes (see [14,21,30,31,37]) and commercial products (Tiggly[1], Osmo[2], Marbotics[3]), but most focus on the whole word approach (e.g. Shadow Box [37], RoyoBlocks [21]), which is ineffective for children struggling with PA and the alphabetic principle.

We identified two systems specifically designed for children with dyslexia [30,31], one designed for non- or hardly speaking toddlers [15] and one designed for preschoolers. SpellBound is a tangible system that supports dyslexic children learning letter-sound correspondences [30]. SpellBound allows children to construct 2D letters by using a set of wooden shapes to form letters. Then, each 2D letter can be placed on a platform to trigger the

[1] https://www.tiggly.com
[2] https://www.playosmo.com
[3] http://www.marbotic.fr/

letter sound and picture of the word. However, this prototype was only sketched out; it has not been developed yet. Also, SpellBound focuses on letter forms and individual sounds rather than the alphabetic rules.

Tiblo uses Lego-like blocks to represent words, numbers, or potential phonemes [31]. Children draw the concept on a piece of paper, attach it to a block, and record a sound for the concept. The blocks have notches that can be connected to represent a word or concept. However, each block in Tiblo contains four notches and may be connected in a non-linear fashion. This is not ideal for learning linear word-building.

LinguaBytes is a tangible system aimed at stimulating Dutch language development for non- or hardly speaking toddlers [14]. This prototype can support a variety of activities related to PA and story reading. In the phonological activity, toddlers learn letter sounds by placing one 3D tangible letter on a customized platform. Audiovisual feedback is provided on a digital display, including 2D words and sounds starting with the same letter. The 3D letters enable letter tracing and the organization of letters in space. However, the design only allows toddlers to learn basic one-to-one letter and sound associations, excluding inconsistent letter-sound mappings in words.

TOK is a tangible language system that helps preschoolers to create their own narratives by manipulating physical blocks. The system is composed of an electronic platform that connects to a tablet, and up to 250 physical blocks with picture cues [38]. Children can place the physical blocks on the platform to view visual elements on the digital screen. Although the system was designed for storytelling, a few PA activities can be supported by using the physical blocks. A study with 20 5-year-old children using TOK with the support of the teacher showed that digital manipulation supported word construction and motivated children's verbal interactions, which contributed to children's PA and lexical knowledge [39]. However, TOK mainly allows for the practice of PA and verbal language rather than the written alphabetic rules.

Three commercial tangible reading systems have been developed. Tiggly is a tangible application that supports 4-8-year-old children in learning vowel sounds and phonics through word-building activity. A child can use the five coloured silicone vowel letters (red *a*, yellow *e*, green *i*, blue *o*, and pink *u*) to interact with the games on an iPad. For example, a child can build the word *cat* by placing the middle vowel letter *a* onto the iPad surface. However, Tiggly only focuses on the practice of vowels, excluding consonants. Furthermore, the colour choices appear to be based on aesthetic considerations rather than theories of the role of multi-modal representations in reading acquisition or empirically validated guidelines. Another popular commercial tangible product, Marbotic, has a very similar game mechanism to Tiggly. However, it uses uppercase letters, which are not commonly used for teaching children at-risk for reading difficulties.

Compared to the design of Tiggly (placing letters on an iPad), the design of Osmo (placing letters on a table) allows for building more complex words containing seven to eight letters and supports the practice of both vowel and consonant letters. Osmo contains an iPad and a set of 2D wooden cards which represent the 26 alphabetic letters. The designers of Osmo intentionally used red and blue colour cues to divide the letter pieces into two groups in order to allow two children to build words together on a table. However, 2D letter cards do not well support letter tracing or manipulating activities. In addition, its colour design was developed based on the consideration of collaboration rather than the learning purpose.

We address this opportunity and knowledge gap by presenting a tangible reading system called PhonoBlocks. We target the alphabetic principle phase (and PA, due to the reciprocal relationship) in early language acquisition. Our goal was to create a system to help 7-to-8-year-old children with poor PA to learn the seven letter-sound rules required to read and spell many words in English. The system's design, particularly its two core design features, dynamic embedded colour cues and 3D tangible letters, were developed based on reading theories and analysis of multisensory reading instructions [10]. PhonoBlocks has the potential to reduce teachers' workload by incorporating (1) a set of word-building games that children can play on their own with system feedback; and (2) a specific training procedure in conjunction with 3D objects so that the system will only give a response in certain conditions (e.g. in consonant blends rule, the first consonant letter *t* will only light up when paired with the letter *h*), which may help inexperienced teachers to teach children.

We first conducted a case study with ten monolingual English-speaking children at-risk for dyslexia using the initial version of PhonoBlocks at a private specialized school in Canada. However, the results showed no consistent learning gains and identified some issues with both system and case study design [7]. The results led us to consult with an early childhood education expert (Hoskyn) who has knowledge of the literature on bi-literacy acquisition and reading interventions for children with learning disabilities. We conducted two expert review sessions with this education expert and then revised the design of PhonoBlocks.

We then conducted a second case study to evaluate the revised system with eight at-risk monolingual English-speaking children 7-8 years old at an urban public elementary school in Canada [11]. The results were encouraging: the at-risk English-speaking children achieved significant learning gains after PhonoBlocks instruction compared to their baseline performances and also maintained their progress one month later after post-test. The results also suggested that design features of our system enabled behaviours that were correlated with learning.

In this paper, we explore if our system can also work for Mandarin-speaking EFL children, and if the results observed in at-risk monolingual English-speaking children can be generalized to another population. We also wanted to explore if (and how) any unique learning behaviours of Mandarin-speaking EFL children can inform our design. We present a case study with ten Mandarin-speaking EFL children around 8 years old using PhonoBlocks, conducted over three weeks at an elementary school in a second-tier city in China. We are interested in ***RQ1****: Do Mandarin-speaking EFL children improve word reading and spelling accuracy after instruction with PhonoBlocks on the words taught in the instruction and similar new words;* ***RQ2****: What are the critical design factors that benefit Mandarin-speaking EFL children in learning to read and spell, and how do they help the children to learn; and* ***RQ3****: What are the similarities and differences of the key finding in RQ2 between the case study with Mandarin-speaking EFL children and the case study with at-risk monolingual English-speaking children.* The results may allow us to make a stronger claim about the feasibility of PhonoBlocks and that its design features may benefit all children with poor PA. The results may also contribute to the design implications for designing TUI reading products specifically for EFL children.

2. System Description

2.1 PhonoBlocks

PhonoBlocks is a tangible system that supports 7-8-year-old children to learn the seven alphabetic rules of English (Fig. 1). The seven rules were validated by an education expert and six reading teachers at a school specializing in teaching children with reading difficulties. They all thought these seven rules were fundamental and important for children to learn. PhonoBlocks is comprised of a touch-based laptop display, a word-making platform with seven slots, and 46 lowercase “hand-sized” 3D tangible letters (including duplicates for common letters). Children learn letter-sound correspondences by placing one or more 3D tangible letters on the platform. Visual feedback is embedded in the 3D letters using LED strips that change colour to indicate sound changes as letters are added or removed. Audio and visual feedback is provided on the digital display. The design rationale of PhonoBlocks can be found at [10].

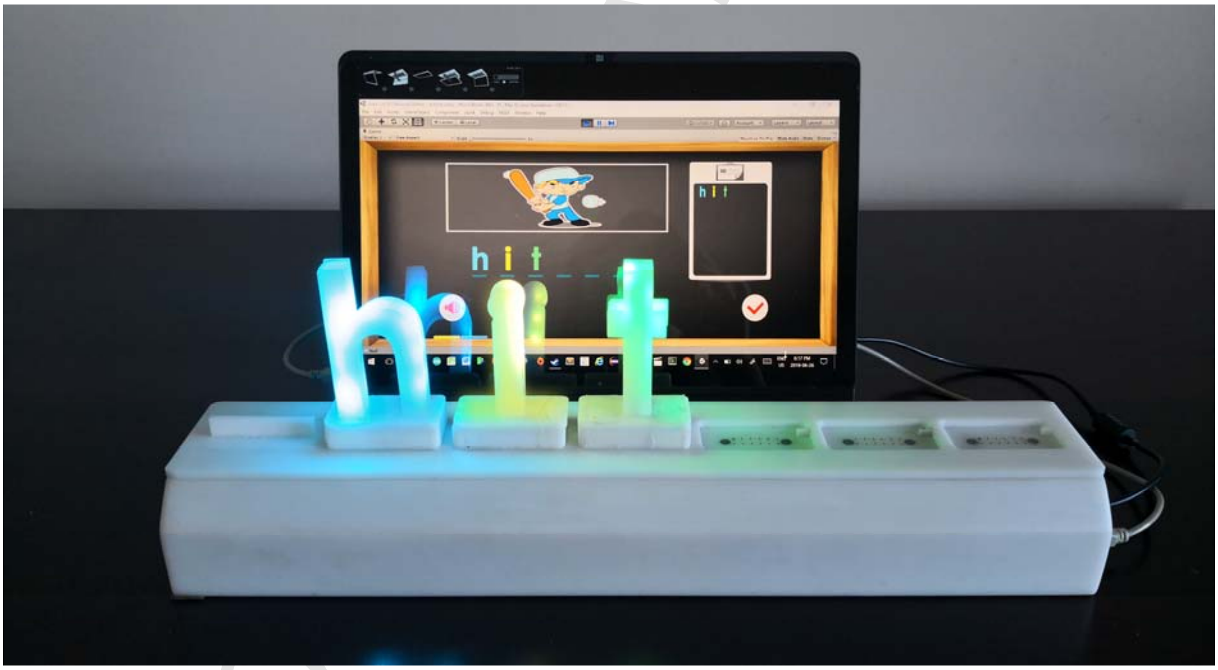

Fig. 1. The PhonoBlocks system: a touch-based display, a platform, and 46 3D tangible letters embedded with LED strips.

PhonoBlocks contains two modes of use. In the Learning Mode, a child learns with the system under the instruction of a teacher. The child or teacher can use the 3D letters to make graphemes, syllables, words, or pseudo-words. The dynamic colour cues are provided within the 3D tangible letters while the associated digital contents are simultaneously shown on the screen, including the coloured 2D letters, letter sound, and picture of the word (if any). The teachers can build any words, even the pseudo-words, as long as they follow the rules (e.g. *sab* in the consonant-vowel-consonant lesson, CVC), and the system will provide the dynamic colour cues. We designed this way because in our previous focus groups, the teachers reported that they sometimes intentionally used pseudo-words to help at-risk children to practice the rules to ensure the children did not just memorize how to read the words. The Practicing Mode allows the child to practice the learned rules on their own. The system plays the word sound and the child spells the word using the letters. If the answer is correct, the child is rewarded with celebrating audio sound and visual stars; otherwise they will get three levels of hints from the system.

The system also has the following basic features: it (1) contains associated word pictures for the word meaning; (2) incorporates a blending/decoding function that allows children to practice blending and decoding skills by swiping right on the display to decode the letters in different colours and hear individual letter sounds or swiping left to blend all the letters together and hear the sound for the whole word; and (3) offers a word history bar that displays the learned words.

2.2 Embedded dynamic colour cues

In addition to the general features, the system has two novel design features: the dynamic cue and 3D tangible letters. We used dynamic colour cues embedded in the 3D letters to explicitly show children the letter-sound correspondences in different word contexts. Each of the seven rules has a unique dynamic colour cue design (Table 1).

Table 1. Seven rule-based activities and colour-coding schemas (black text = white LED light; grey text = LED off.)

Rules	**Explanation of rules**	**Sequence of interaction (word example)**	
		Dynamic colour cues	**Blending/decoding function**
CVC	Learning that there are *three* letter sounds in the CVC words	*bet*	*bet*<—>*bet*
Consonant blends	Learning that two consonant letters make a *blended* sound	*f*->*fl*->*flag*	*flag*<—>*flag*
Consonant digraph	Learning that *two* consonant letters only make *one* sound	*s*->*sh*->*shop*	*shop*<—>*shop*
Magic-e rule	Learning that the vowel sound will change from short to long when a letter *e is* added at the end of a CVC word, and the letter *e* is silent	*gam*->*game*	*game*<—>*game*
Vowel team	Learning that *two* vowel letters make *one* sound—the sound of the *letter name* for the first vowel letter	*e*->*ea*->*eat*	*eat*<—>*eat*
R-controlled vowel (*not used in this study*)	Learning and automating the stable units of *ar*, *er*, *ir*, *or*, *ur* sounds	*c*->*ca*->*car*	*car*<—>*car*
Syllable division	Learning to divide multiple syllables within a word	*water*—> *water*	*water* <—>*water*

Specifically, in the CVC lesson, we used three colours (blue, yellow, and green) to represent the *three* letter sounds within a CVC word. In the consonant blends lesson (e.g. *fl, st, tr)*, we made both consonant letters quickly change to green when paired, to indicate the two sounds blending together. In the consonant digraph lesson (e.g. *th*, *ch*, *sh*), only the first consonant lights up (green) when two consonants are paired. In this way, we attempted to highlight that two consonant letters put together make one sound. Since the vowel team (e.g. *ea*, *ai*, *oa*) and r-controlled vowel (e.g. *ar, ur*, *or*) lessons share a similar principle but with vowel letters, we used the same design strategy while having the light turn red instead of green. In the magic-e lesson (e.g. *gam-game*, *tap-tape*), we made the vowel letter change from yellow to red to indicate the vowel sound changes from short to long when a trailing *e* was added (Fig. 2). In the syllable division lesson (e.g. *water-wa/ter, creepy-cree/py*), we first made all letters pink, and then used unique colours to represent each syllable within a word. In each rule, we used colour flashes to draw children's attention to the moment of colour change. We also made the default colour white for letters irrelevant to the rule to better attract children's attention to important letters in each rule.

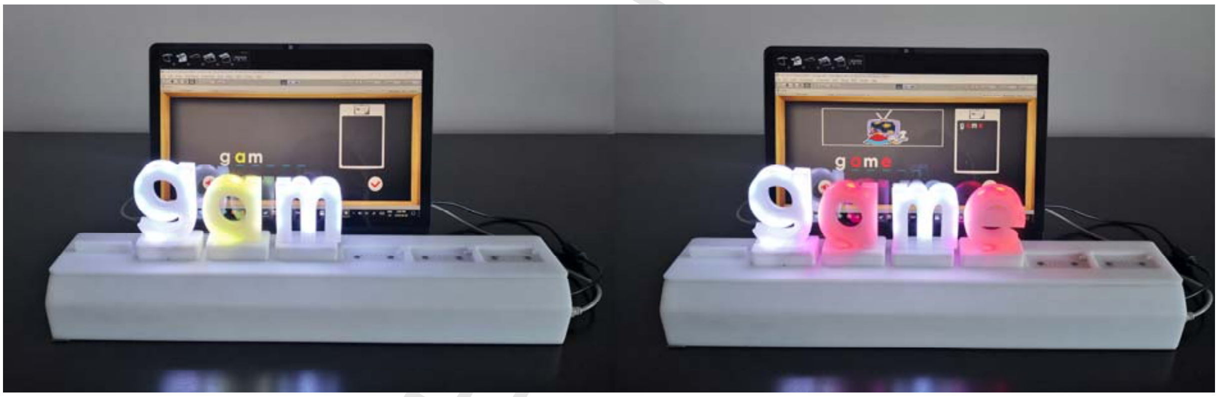

Fig. 2. The letter *a* flashes three times to change from yellow to red when a letter *e* is added in the magic-e lesson

In order to support colour cues, each letter contains a programmable LED strip. We have adjusted the illumination of the LED lights to ensure users can see and distinguish the colours in either a dark environment or in daylight.

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2.3 3D tangible letter forms

We use sturdy, hand-sized 3D tangible letter forms to facilitate letter tracing and manipulation activities (Fig. 3). We use physical constraints–a notch in each letter helps children to learn the orientation of mirrored letters (e.g. *p*, *d* or *b* can only be placed correctly due to the notch).

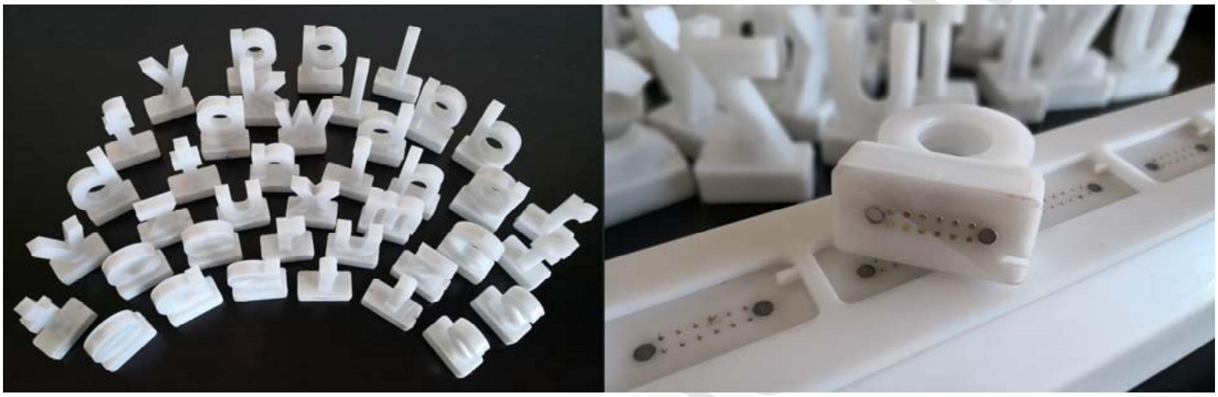

Fig. 3. 3D tangible letters with physical constraints which can be placed into a slot of the word-building platform.

3. Methodology

3.1 Research design

We used a case study design with a pre- and post-test component to address these research questions. We did this for two main reasons: (1) our studies are more exploratory because we are interested to see how Mandarin-speaking EFL children use PhonoBlocks and whether their learning performances and interactional behaviours are similar (or not) to those of the at-risk monolingual English-speaking children [7]; and (2) understanding the relationship between children's learning performance and interactional behaviours with the system requires mixed data sources and detailed examination of evidence, an approach supported in group and individual case-by-case analysis.

In our larger project that explores children's use of PhonoBlocks, we designed *embedded multiple case studies* with at-risk monolingual English-speaking children and Mandarin-speaking EFL children [49]. We selected the two cases because in both, the children may have poor PA and may have difficulties in learning to read and spell English using the traditional class-based approach. For each case, we analyzed data at two levels of unit analysis: group and individual. At each unit level, we looked for evidence of learning gains and related interactional behavioural patterns with our system that may be correlated to learning. In this paper, we focus on the Mandarin-speaking EFL children case study, report results for the two unit levels of analysis (group and individual) and compare results to the previous case study of Monolingual English-speaking at-risk children.

3.2 Participants

The school teacher recruited ten Mandarin-speaking EFL children, with an average age of 8.1±0.3 years old and studying at an elementary school located in Taiyuan, China, to participate in our study. The participants were selected based on the following criteria: (1) they were children with limited learning resources outside of the classroom and who looked for new learning opportunities; and (2) they had basic letter name/sound knowledge but had limited reading and spelling knowledge of the words taught in the PhonoBlocks instruction. The teachers informed children and parents about the learning opportunity and interested parents contacted us directly by phone. There were four boys and six girls. All the participants were Chinese and their first language was Mandarin. We screened each child's current knowledge of English to ensure they could read and spell at least parts of the 26 letters of the alphabet but had minimal knowledge of how to read and spell words using the six rules to be taught (excluding the r-controlled vowel lesson, for reasons given below).

3.3 Learning tasks

The learning tasks were six rule-based lessons, including: CVC, consonant blends, consonant digraph, magic-e rule, vowel team, and syllable division. We did not incorporate the r-controlled vowel lesson because the education expert and the school teacher both suggested that it might be difficult for Chinese children to learn to pronounce the *r* sound in such a short training period. The CVC and magic-e lessons comprised two training sessions, while the rest of the lessons comprised only one. This was because the CVC and magic-e lessons focused on vowel sounds, where two sessions were required to introduce different vowels and their respective sounds. All the children received a total of eight individual training sessions. They learned three words in each session (e.g. *bet*, *dad*, *tin*, called the "trained words"), for a total of 24 trained words over eight sessions. We developed the lesson plans and word lists based on previous research [4] and suggestions from the education expert and the school teacher. The education expert helped us to organize the six lessons and select the appropriate words for each lesson. We then worked with the school teacher to examine if all the words are appropriate for the children to learn.

In order to examine whether the children remembered trained words, we tested their reading and spelling accuracies on 24 trained words (3*8) for reading and seven trained words for spelling. We only selected a subset of words in the spelling test because the teacher told us that the children might lose patience if they were asked to spell all 24 trained words. Therefore, we only selected some of the representative words from each lesson (two from CVC and one from each of the remaining lessons). In order to examine if they could transfer the rules to other similar words, we tested 24 (new) untrained words for reading and seven untrained words for spelling that followed the same rules in a post-test (Appendix A).

3.4 Procedure

Prior to using our system, the children received a pre-test for baseline assessment (see details under *Data collection and analysis*, below). All pre-tests were individually administered by a research facilitator in a quiet room at the school, taking 20 minutes for each child. Then each child received eight one-to-one training sessions facilitated by a trained research facilitator in a quiet room after school, three to four times a week over a three-week period. The facilitator can speak fluent English and Mandarin. She was trained by the education expert beforehand, and they co-developed the teaching protocol. Each training session was approximately 20 minutes long, including 15 minutes of instruction with the facilitator and five minutes of the child practicing with the system. During instruction, the facilitator used an explicit phonics-based approach to direct children's attention to letter-sound correspondences and teach the alphabetic rules [4]. During practice time, the children had to complete the spelling tasks using the system by themselves. The facilitator only provided technical support if needed (e.g. making sure a letter was fully inserted into its slot). The post-test was conducted immediately after all eight sessions were done. Each child’s word reading and spelling accuracies were assessed individually by the facilitator.

3.5 Data collection and analysis

Our mixed-methods approach involved collecting and analyzing multiple sources of data. During the pre-test, the participants were asked to read the list of 24 words they were going to learn to read (trained reading words). The words were presented on a computer screen. They were also asked to spell on paper the seven words they were going to learn to spell (trained spelling words). A score of 1 was given for each correct word and a score of 0 for each incorrect word, and the raw accuracy scores for trained reading and spelling were recorded as a baseline (e.g. 8/24, 3/7). During each training session, before instruction began, the participants were again asked to read the list of 24 trained words presented on a computer screen and the raw accuracy reading scores or any changes in reading performance were recorded. The participants received the post-test immediately after completing all eight raining sessions. During the post-test, the participants were asked to read the same 24 (now trained) words and 24 (new) untrained words presented on a computer screen and to spell seven trained and seven (new) untrained words on paper. The accuracy scores were recorded. We also collected data about the children’s interactional behaviours using video recording and structured observational note sheets written by the facilitator.

We primarily used quantitative methods to address the ***RQ1***, including using correlated *t*-tests to determine the differences between the pre- and post-tests in the means of the raw scores of reading and spelling accuracies on trained and untrained words. We also supplemented quantitative findings with thematic analysis of the observational data about the individual children's reading performance and spelling error patterns, as well as follow-up feedback from the school teacher and the children's parents after the study. We also used thematic analysis to address the ***RQ2***, including identifying from video data and observational notes the common and interesting patterns of interaction that learning theories predicted were beneficial for learning. In addition, we used thematic analysis to address the ***RQ3***, including comparing the main results of *RQ2* to those in the study with at-risk monolingual English-speaking children [11].

4. Results

4.1 Children's reading and spelling gains

For reading, the participants made large improvements in reading accuracy on trained words from the pre-test to the post-test. Paired sample t-test results showed that there was a statistically significant increase at the $p<0.001$ level in participants' raw accuracy scores on trained word reading accuracy between the pre- and post-tests, increasing from 1.3±1.7 words to 22.5±1.3 words out of 24 trained words in total (t (9) = 38.283, p <0.0005, d=12.1[4]). The participants transferred their new reading knowledge to the untrained words. Results showed that there was no statistically significant difference in participants' raw accuracy scores on the post-test reading improvement between the trained and untrained words (t (9) =1.000, p=0.343). The mean of children's raw scores for the trained and untrained words were 22.5±1.3 and 22±2.1 out of 24 trained/untrained words respectively in the post-test. This means that the participants transferred their learning gains from trained words to similar but non-taught or untrained words.

For spelling, the participants also improved on the spelling accuracy of trained words. Results showed a statistically significant increase at the $p<0.001$ level in participants' scores on trained word spelling between the pre- and post-tests, increasing from 0 word to 3.5±1.8 words out of seven trained words in total (t (9) =6.220, $p<0.005$, d=2.0). The participants transferred some of their new spelling knowledge to the untrained words. Results showed a statistically significant increase at the $p<0.001$ level in participants' scores between the pre-test trained words and the post-test (new) untrained words (t (9) =4.636, $p<0.005$, d=1.5). The mean of raw scores increased from 0 words to 1.7±1.2 words out of seven trained/untrained words. Results also showed a statistically significant difference at the $p<0.001$ level on the post-test spelling improvement between the trained and untrained words (t (9) =4.630, $p<0.005$, d=1.5), indicating that the participants did not fully transfer their spelling skills from trained words to untrained words. The reason may partially because our instruction focused more on reading and spelling with tangible letters rather than spelling and writing letters on paper.

Our observational data showed that four EFL children (P1, P2, P7, and P10), who had initial difficulties in reading similar vowel sounds (/e/, /a/ and /i/), gradually increased their reading accuracy and speed in reading the vowel sounds in trained words, although we observed that they still could not master these vowel sounds after the instruction (i.e. they were slow in reading untrained words and sometimes made errors). The reason may be partially because these vowel sounds do not exist in Chinese phonemes. We also observed that almost all children (except P8) started to use a phonetic approach to reading words that they were uncertain of. Even though a few children sometimes had difficulty in blending sounds for untrained words, at least the children used the correct strategy to decode words rather than using memorization of words by visual shapes as shown in the pretest.

The analysis of children's spelling error patterns also demonstrated their spelling improvement. For example, none of the EFL children could spell any letters of the words in the pre-test. In the

[4] Effect sizes: d>=0.8 large, d>=0.5 medium, d>=0.2 small.

post-test, despite some mistakes, the children could spell parts of the letters in words. For example, almost all the children could correctly spell the CVC pattern, despite the vowel errors. In the consonant digraph lesson, nine children (except P2) correctly spelled the pattern *sh* in the trained word *shop* and untrained word *ship*. In the magic-e lesson, five children (P1, P4, P5, P6 and P10) could correctly spell the CVC+e pattern.

Although we did not conduct formal interviews with the school teacher and parents, we did receive their follow-up feedback in person about children's learning gains. The school teacher mentioned that two children's reading accuracies were improved from below the average level to the average level after PhonoBlocks instruction. Six parents and their children also asked if we would conduct any future studies with PhonoBlocks and explicitly expressed their strong willingness to continue participating in these studies. Four parents told us that their children's self-esteem and learning motivation increased after PhonoBlocks instruction. Without controlling other factors, we could not make a strong claim that the changes related to learning were due to PhonoBlocks instruction. However, because the participants had failed to progress with previous instructions and progressed after the PhonoBlocks intervention, it is likely that PhonoBlocks was associated with their new found progress. This warrants further study.

The claims we can make based on quantitative findings of *group level* reading and spelling accuracy gains are limited by the small sample size (10 children). To supplement these findings we also present in-depth qualitative observation data focusing on changes in children's performance and unique interactional behaviours at both *group and individual levels*, which may be correlated with learning.

4.2 Beneficial design features of PhonoBlocks

4.2.1 Dynamic colour cues

Most participants were attracted to the embedded dynamic colour cues. For example, in the CVC lesson, P2 asked, “What the colour will be in the fourth slot?” When he first saw the colour change in the tangible letters in the magic-e activity, he said with a puzzled face, “Wow!” Similarly, P1, P3, and P10 also had excited expressions on their faces when they saw colour changes. We interpreted our observations as indicating that the children's attention was on the embedded dynamic colour cues.

The flashing colour is important because it helps to draw children's attention to the moment when placing a letter changes the sound of the whole word. For example, we observed that the yellow and red vowel flashes encouraged the children to notice the vowel sound changes when an e was added in the magic-e rule. The facilitator asked P1, "What did you see?" P1 said, “light flashes." The facilitator continued, asking, "What does that mean?" P1 said, "The red colour means letter name, and the yellow colour means letter sound.” After the post-test, many participants (P1, P3, P5, P7, and P8) self-reported that they really liked the colour flashing in the magic-e lesson, and they could clearly tell what the dynamic colour cues represented after a two-week gap (e.g. “The red colour means letter name, and the yellow colour means letter sound.”).

The participants were able to quickly learn what the dynamic colour cues represented. For example, in the consonant blends lesson, after being told the green colour meant the two consonant sounds were blended together, many participants (P3, P6, P7, P9, and P10) were observed intentionally sounding out the pairs together (e.g. /fl/, /cr/) when they saw the letters change to green.

4.2.2 3D Tangible Letters

We observed that the participants simultaneously used multiple senses in learning to read and spell. For example, P6 placed each letter on the platform and spoke its individual letter sound for the word *flag* (*fl-a-g*). We also noticed that most participants (P1, P3, P4, P7, P9, and P10) actively used multiple senses to help them solve the tasks during practice. For example, when P1 was asked to make the word *hit*, she often kept sounding out the /i/ sounds when looking for the tangible letter *i*. Several participants also traced mirrored letters when they seemed confused and hesitated in selecting them (Fig. 4).

Fig. 4. P5, P6, and P8 traced the tangible letters during the instruction.

The participants quickly learned to use the physical constraints (notch) to determine correct letter orientation. For example, many participants (P1, P2, P3, P5, P9, and P10) looked at the notch of the tangible letters to determine the correct letter orientation. Some participants (P4 and P7) tried out the tangible letters with the system to see whether they could be fitted or not. The participants also realized that the orientation matters more for several letters than for others. For example, when P2 found that the letter *w* could not fit into the slot, he said, "I put the *w* backwards." Then he switched its direction and placed it into the slot. However, the orientation of the mirrored letters was different. In the consonant blends lesson, when asked to make the word *crab*, P5 picked up the letter *d* but found it did not match to the slot. Eventually she took off the letter *d*, selected the letter *b*, and slotted it into the platform.

We observed that several children (P2, P3, P7, and P10) developed two ways to organize tangible letters in space to make their tasks easier to solve. First, two participants (P2 and P10) placed the tangible letters in a line, which appeared to help them to visually and physically find certain letters. Second, two participants (P3 and P7) liked to pick up the tangible letters that they were going to use later and set them aside (Fig. 5). For example, when making the word *shop*, P7 first selected the four letters he needed to use, placed them in front of him, and then put them onto the platform.

Fig. 5. P7 placed the letters *c*, *h*, *i*, and *p* in front of him when making the word *chip* (*left*); P7 placed the letters *s*, *h*, *o*, and *p* in front of him when making the word *shop* (*right*).

We noticed that most participants placed letters one by one when they were learning a rule, but once they understood the rule, they placed pairs of letters with two hands. For example, when P3 was asked to make the word *flag*, he simultaneously picked up the letters *f* and *l* using two hands. However, when asked to make the word *stop*, he first placed the letter s in the second slot, thought for a while, and then placed the letter *t* in the first slot (Fig. 6). This pattern (two hands for known pairs and single hand for unknown pairs) was observed frequently with P1, P2, P3, P6, P7, P9, and P10 when they were making words that contained consonant blends, consonant digraphs, and vowel teams (Fig. 7).

Fig. 6. When P3 understood the *fl* pair in the word flag, he picked up the letters *f* and *l* simultaneously using two hands (*left*); when he was unsure about the *st* pair, he placed the *t* and *s* separately (*middle* and *right*).

Fig. 7. P2 (*left*), P5 (*middle*), and P7 (*right*) used two hands to place the vowel team (*ea*) and consonant digraph (*th*).

4.2.3 Other Design Features

We observed that the participants often checked the corresponding picture for each word. P1, P2, P5, and P10 always guessed what the learned words meant based on the pictures. For example, when P2 saw the picture of the word *game*, he smiled and said, “Computer game.” When he saw the picture associated with the word *late* (a clock shows a man running late), he asked, “Does it mean clock?” After the facilitator explained, he understood it.

The participants also said that they enjoyed playing on their own in the Practicing Mode. For example, during the instruction, P2, P5, and P10 said that they would like to play more with the games. The participants were very excited to hear the rewarding sounds and pictures when they successfully completed the tasks. P1, P3, P7, and P10 always smiled when they heard the rewarding sounds from the system.

Many participants (P1, P3, P5, P7, P9, and P10) often looked at the words they already learned when making new words. The word history bar served as an additional hint when they did the spelling tasks.

4.3 Cross-case analysis

4.3.1 Summary of main results with at-risk monolingual English-speaking children

In the previous study, we conducted a case study with eight at-risk monolingual English-speaking children 7-8 years old to look at how they used the PhonoBlocks system in an urban public elementary school in Canada [11]. The learning tasks were six rule-based lessons: CVC, consonant blends, consonant digraph, magic-e rule, vowel team, and r-controlled vowel. Each rule-based lesson involved two 20-minute individual sessions, for a total of 12 sessions altogether for each child. Children worked with a trained facilitator to learn three words in each session, for a total of 36 trained words over 12 sessions. We conducted pre-, post- and follow-up tests to examine the participants' reading and spelling accuracies on both trained and untrained words. We also collected observational data and video data on children's learning behaviours during the PhonoBlocks instruction.

The pre-, post- and follow-up testing results showed that at-risk English-speaking children achieved significant learning gains after PhonoBlocks instruction compared to their baseline performances and also maintained their progress one month later after post-test. The qualitative results suggested that dynamic colour cues with flashing colours had several benefits: (1) It attracted children's attention to the sound change moment; (2) it was easy for children to understand the represented meanings of the dynamic colour cues; and (3) it allowed children to detect spelling errors through unexpected colour changes. The 3D tangible letters enabled activities such as letter organization in space, comparison of letter shape, and one-handed or two-handed manipulation of letters. These actions may make the spelling tasks easier compared to printing words on paper [11].

4.3.2 Comparative results regarding beneficial design features

In both case studies, we identified three main similarities in the results concerning the beneficial design features. First, we observed that the participants in both studies were attracted to and engaged with the flashing dynamic colour cues and they were able to understand or quickly learn what these cues represented. Second, the results in both studies showed that 3D tangible letter forms with a physical notch enabled various actions that may simplify the spelling tasks. Third, both results indicated that participants' hand actions with the 3D tangible letters mirrored their understanding of how letters make sounds.

We also identified three main ways in which the design features impacted the two groups differently. First, we noticed that the at-risk monolingual English-speaking children frequently used the dynamic colour cues to detect spelling errors, while the Mandarin-speaking EFL children rarely did. Second, the at-risk children could quickly understand the word meaning based on the word sound. However, the EFL children had very minimal oral vocabularies and could not understand word meanings. Instead, they attempted to guess the meaning based on the associated picture cue, which sometimes led to misinterpretation. Third, compared to the at-risk children who developed various strategies to manage letters in space for demanding learning activities (e.g. separating vowels and consonants in the vowel team session, and placing all the vowel letters together followed by a *r* letter in the r-controlled vowel session), the EFL children developed fewer strategies to organize letters in space.

5. Discussion

The results in general suggest that PhonoBlocks can be used to support Mandarin-speaking EFL children at the level of PA to learn to read and spell English words. We discuss three design implications of tangible reading systems that are applicable for all children who start to read and spell (5.1, 5.2, 5.3). We also discuss three design implications that are uniquely applicable for EFL children (5.4, 5.5, 5.6).

5.1 Use embedded dynamic colour cues with flashing to attract attention

The embedded dynamic colour cues with flashing successfully drew children's attention to the moment where one letter changes the sound of the rest of the word. Compared to the traditional O-G approach that uses static colours, we used dynamic colour cues to represent various letter-sound correspondences within word contexts. Compared to other reading systems that use different colours for each letter for vowels and consonants (e.g. Tiggly and Osmo), our approach used only a small number of colours to highlight parts of words (groups of letters), which helps to draw attention to the letters that are important in each rule.

It is challenging to determine how to design dynamic colour cues for new rules. We propose the following design recommendations: (1) using a limited number of colours and only colouring the important letters in a rule, which can better attract children's attention to the relevant parts of the rule; (2) colour selection should follow the conventional colour scheme used in educational practice, such as using cold colours (e.g. blue and green) for consonants and warm colours (e.g. red and orange) for vowels [11,45]; and (3) the design of colour change and flashes should follow the instructional method used by school teachers. For example, our focus groups indicated that the teachers taught at-risk children the consonant blends rule by first sounding out the first consonant letter (e.g. *f*), and then quickly sounding out the two letters (e.g. *fl*). We therefore used blue to highlight the first letter sound, and then made both letters change to green to represent the blended state.

5.2 Create 3D tangible letter forms and workplace to enable epistemic actions that simplify reading and spelling tasks

Epistemic actions are actions used to change external elements in the world in order to simplify a task [20]. Previous research suggested that TUIs encourage more epistemic actions compared to GUIs [2], and enable epistemic actions in the context of storytelling [38]. Our results showed that 3D tangible letter forms enabled various types of epistemic actions in reading and spelling tasks (e.g. pairing and ordering). These epistemic actions helped the children to shift a mental task to a visual-physical task (cognitive offloading) so that they could focus on understanding the alphabetic rules rather than on how to write letter shapes [2].

In order to support children's epistemic actions in learning to read and spell, the following design elements of 3D tangible letters need to be considered: (1) they should be hand-sized and crafted with light and safe material so that children can easily pick up and hold them in their hands; (2) letters must be able to stand up on their own so that the children can easily organize them in space; (3) there should be enough space on the table to place all the letters; and (4) they should have both physical constraints (usually on the bottom) and visual marks (on the top) which allow the children to quickly recognize and orient them in space.

5.3 Use 3D forms and tasks that enable hands-on interaction, which improves attention and makes learning visible

The stand-alone 3D letters should also be light, pleasant to touch, and easy to move, organize and handle. Providing a small subset of letters for each learning task and encouraging both teacher and child to handle them (e.g. place in slots) helps focus attention on the letters. This is consistent with previous theories that showed the use of kinaesthetic/tactile modalities could improve learners' attention and memory [10,20]. If letters are light and sturdy, letters not in use can easily be moved away with an arm swipe. If letters are easy to handle, children can use both one-handed and two-handed interactions, which reflects their understanding of letter-sound structures and enables a facilitator to see learning in real time and provide appropriate feedback.

5.4 EFL: Focus on vowel sounds and adjust between "coarse" and "fine" colour-coding strategies based on different needs

We noticed that Mandarin-speaking EFL children rarely used dynamic colour cues to detect spelling errors. This may be because most of their errors were on vowel sounds, which could not be detected through the current design. In PhonoBlocks, we used the "coarse" colour-coding strategy to highlight the rules rather than the similar sounds [7]. For example, in both CVC (*bet*, *dad*) and magic-e lessons (*gam* →*game*, *tap* →*tape*), which contained vowel sounds, all the short vowels were coloured yellow while all the long vowels were coloured red. The strategy works well to help children understand the rules, but it may be insufficient to distinguish similar vowel sounds.

We suggest that designers could consider using both "coarse" and "fine" colour-coding strategies to adapt to EFL children's needs at various learning stages. For example, when teaching the CVC rule, the "coarse" colour strategy can be applied to highlight the rule in general (*bet*, *dad*). Once children understand the rule, the system could then switch to the "fine" colour strategy in which each vowel is associated to a unique colour (*bet*, *dad*). Learning to read is a cognitive developmental process in which children need to pass through each stage (gradually moving roughly from the pre-alphabetic stage, to the partial–alphabetic stage, to the full-alphabetic stage) to develop accurate and fluent word reading abilities [9]. Our dynamic embedded colour cue design can be easily adjusted to satisfy children's various needs at different stages or a particular need (e.g. vowel difficulties) at one stage.

5.5 EFL: Start with words that have concrete meaning and carefully design culturally appropriate pictures for the words

EFL children have usually have limited oral vocabulary and may rely more on visual cues such as word pictures. Therefore, the learning content should start with words containing concrete meaning. The design of word pictures should be easy to understand and closely related to the core meaning of the words to avoid misinterpretation. Supplementary animation or bilingual audio instruction can be used. Designers should also consider cultural context when designing picture cues for EFL children who have less background knowledge of English.

5.6 EFL: Support tangible tools that encourage organizational strategies

The results showed that EFL Mandarin-speaking children developed fewer organizational strategies compared to at-risk children. EFL children had less English proficiency, which may limit their improvising activities with the tangible letters. Designers could consider providing additional tools to encourage EFL children's organizational actions. For example, unique letter storages can be designed for different lessons. In the CVC lesson, the storage could contain three separate spaces; one each for the *first consonant*, the *vowel*, and the *last consonant* letters. In the vowel team lesson, storage with two spaces can be provided, with one for *vowel* and the other for *consonants.* Teachers can use the tools to prompt EFL children to think about how to effectively organize letters in space.

We believe the design guidance for the colour cues and 3D letters are not only useful for at-risk monolingual English-speaking and Mandarin-speaking EFL children, but may also be beneficial to all other children who need to learn to read and spell. Although we only investigated Mandarin-speaking EFL children, the design considerations for EFL children may also work for other EFL children whose first language is not Mandarin or for ELL children who learn English as a foreign language in English-speaking countries.

6. Limitations

The main limitation is the case study design with a small sample size and no control group. The small size makes it difficult to generalize results. The lack of a comparative control group (one-to-one traditional O-G program) makes it difficult to gauge the effectiveness of our system. We do not know if the learning gains were due to the one-to-one PhonoBlocks instruction or other factors. However, we provided detailed qualitative results on children's learning behaviours and interactional behaviours which may be correlated with learning. It was encouraging to see that significant learning gains and several of the learning behaviours were also observed in at-risk monolingual English-speaking children who were reported to fail to progress with both the teacher's class instruction and the extra one-to-one intervention provided by the resource teacher at the school. The results of both case studies suggest that PhonoBlocks is promising in supporting learning to read and spell for children with poor PA and limited knowledge of the alphabetic principle. In the future, more wide-scale controlled experiments with at-risk and EFL children would enable us to make stronger claims about the effectiveness of our entire system.

7. Conclusion

We present a design case study with ten Mandarin-speaking EFL children using a tangible reading system called PhonoBlocks in learning to read and spell. The results showed that the EFL children achieved significant learning gains relative to their baseline performance. These results, combined with our qualitative analysis of the ways the children interacted with the system, suggest that the core design features of TUIs positively impacted learning. We compared the results with the results from a different case study with at-risk monolingual English-speaking children using PhonoBlocks. We discuss the design implications for designing for children with poor PA and limited knowledge of the alphabetic principle, and particularly for children who learn English as a foreign language.

The main contribution of this work is that it suggests that tangibility matters in learning to spell for children. Reading is, in part, spatial. Tangible letters make it easy for children to position the letters and hear associated sound changes. Because computation can be embedded in these tangible letters, they can also change their colour in response to their position in the word, drawing a child's attention to the moment where one letter changes the sound of the rest of the word. Tangibility also matters because the physicality of tangible letters means that children can use epistemic strategies, such as pairing and ordering, to make the task of spelling words easier than if they were printing words on paper. The act of spelling is separated from the act of printing. Taken together, embeddedness and physicality mean that children's letter manipulation, attentional focus, and use of epidemic strategies make the task of learning basic spelling rules easier. Over time, children will learn and memorize these foundational spelling rules and the tangible system will no longer be necessary. Our work contributes to design recommendations which are applicable to the design of reading TUIs for typical, at-risk, and EFL/ELL children.

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References

[1] A.N. Antle, The CTI Framework: Informing the Design of Tangible Systems for Children, in: Proc. 1st Int. Conf. Tangible Embed. Interact., ACM, New York, NY, USA, 2007: pp. 195–202.

[2] A.N. Antle, Exploring how children use their hands to think: An embodied interactional analysis, Behav. Inf. Technol. 32 (2013) 938–954.

[3] K. Apel, What is orthographic knowledge?, Lang. Speech Hear. Serv. Sch. 42 (2011) 592–603.

[4] V.W. Berninger, R.D. Abbott, D. Zook, S. Ogier, Z. Lemos-Britton, R. Brooksher, Early Intervention for Reading Disabilities Teaching the Alphabet Principle in a Connectionist Framework, J. Learn. Disabil. 32 (1999) 491–503.

[5] P.D. Bunce, Alphabet headaches Hong Kong’s English literacy challenge, (2007).

[6] P. Chiappe, L.S. Siegel, A. Gottardo, Reading-related skills of kindergartners from diverse linguistic backgrounds, Appl. Psycholinguist. 23 (2002) 95–116.

[7] E.S. Cramer, A.N. Antle, M. Fan, The Code of Many Colours: Evaluating a Dynamic Colour-Coding Scheme in a Tangible Spelling System for Children with Dyslexia, in: Proc. 15th Int. Conf. Interact. Des. Child., ACM, Manchester, UK, 2016: pp. 473-485.

[8] S. Dehaene, Reading in the Brain: The New Science of How We Read, Penguin, 2009.

[9] L.C. Ehri, Orthographic Mapping in the Acquisition of Sight Word Reading, Spelling Memory, and Vocabulary Learning, Sci. Stud. Read. 18 (2014) 5–21.

[10] M. Fan, A.N. Antle, E.S. Cramer, Design Rationale: Opportunities and Recommendations for Tangible Reading Systems for Children, in: Proc. 15th Int. Conf. Interact. Des. Child., ACM, New York, NY, USA, 2016: pp. 101–112.

[11] M. Fan, A.N. Antle, M. Hoskyn, C. Neustaedter, E.S. Cramer, Why tangibility matters: A design case study of at-risk children learning to read and spell., in: Proc. Conf. Hum. Factors Comput. Syst. CHI ’17, ACM Press, Denver, CO, USA, 2017: pp. 1805-1816.

[12] L. Farokhbakht, D. Nejadansari, The effect of using synthetic multisensory phonics in teaching literacy on EFL young learners’ literacy learning, Int. J. Res. Stud. Educ. 4 (2015).

[13] E. Geva, A. Massey-Garrison, A Comparison of the Language Skills of ELLs and Monolinguals Who Are Poor Decoders, Poor Comprehenders, or Normal Readers, J. Learn. Disabil. 46 (2013) 387–401.

[14] B. Hengeveld, C. Hummels, H. van Balkom, R. Voort, J. de Moor, Wrapping Up LinguaBytes, for Now, in: Proc. 7th Int. Conf. Tangible Embed. Embodied Interact., ACM, New York, NY, USA, 2013: pp. 237–244.

[15] B.J. Hengeveld, Designing LinguaBytes: A tangible language learning system for non-or hardly speaking toddlers, (2011). Doctoral Dissertation, Eindhoven University of Technology. Retrieved from 10.6100/IR715535.

[16] X. Hu, 农村小学英语教师素质情况调查及分析—以黑龙江为例 [Investigating qualifi - cations of English teachers in primary schools in Heilongjiang province], 中国成人教育. 18 (2009) 89–90.

[17] S. Jubran, Using multi-sensory approach for teaching English skills and its effects on students’ achievement at Jordanian schools., Eur. Sci. J. 8 (2012) 1857–1881.

[18] M. Kast, M. Meyer, C. Vögeli, M. Gross, L. Jäncke, Computer-based multisensory learning in children with developmental dyslexia, Restor. Neurol. Neurosci. 25 (2007) 355–369.

[19] K. Kelly, S. Phillips, Teaching Literacy to Learners with Dyslexia: A Multi-sensory Approach, SAGE, 2011.

[20] D. Kirsh, P. Maglio, On distinguishing epistemic from pragmatic action, Cogn. Sci. 18 (1994) 513–549.

[21] J. Kleiman, M. Pope, P. Blikstein, RoyoBlocks: An Exploration in Tangible Literacy Learning, in: Proc. 12th Int. Conf. Interact. Des. Child., ACM, New York, NY, USA, 2013: pp. 543–546.

[22] A.S. Lillard, Preschool children's development in classic Montessori, supplemented Montessori, and conventional programs, J. Sch. Psychol. 50 (2012) 379–401.

[23] H. Lin, 浙江省小学英语教师素质调查 [An investigation on qualifi cations of primary school English teachers in Zhejiang province], 浙江师范大学学报,. 30 (2005) 82–85.

[24] C. McBride-Chang, C. Suk-Han Ho, Predictors of beginning reading in Chinese and English: A 2-year longitudinal study of Chinese kindergartners, Sci. Stud. Read. 9 (2005) 117–144.

[25] D. McGuinness, C. McGuinness, J. Donohue, Phonological training and the alphabet principle: Evidence for reciprocal causality, Read. Res. Q. (1995) 830–852.

[26] D. Mioduser, H. Tur-Kaspa, I. Leitner, The learning value of computer-based instruction of early reading skills, J. Comput. Assist. Learn. 16 (2000) 54–63.

[27] S.B. Mocan, T.L. Leacock, S.B. Mocan, T.L. Leacock, Using Fast ForWord® to Support Learning to Read: A Review of the Literature, in: 2009: pp. 989–997.

[28] R. Nicolson, A. Fawcett, M. Nicolson, Evaluation of a computer-based reading intervention in infant and junior schools, J. Res. Read. 23 (2000) 194–209.

[29] T. Oakland, J.L. Black, G. Stanford, N.L. Nussbaum, R.R. Balise, An Evaluation of the Dyslexia Training Program A Multisensory Method for Promoting Reading in Students with Reading Disabilities, J. Learn. Disabil. 31 (1998) 140–147.

[30] S. Pandey, S. Srivastava, SpellBound: A Tangible Spelling Aid for the Dyslexic Child, in: Proc. 3rd Int. Conf. Hum. Comput. Interact., ACM, New York, NY, USA, 2011: pp. 101–104.

[31] S. Pandey, S. Srivastava, Tiblo: A Tangible Learning Aid for Children with Dyslexia, in: Procedings Second Conf. Creat. Innov. Des., ACM, New York, NY, USA, 2011: pp. 211–220.

[32] A. Pasquarella, X. Chen, A. Gottardo, E. Geva, Cross-language transfer of word reading accuracy and word reading fluency in Spanish-English and Chinese-English bilinguals: Script-universal and script-specific processes, J. Educ. Psychol. 107 (2015) 96–110.

[33] L. Rello, R. Baeze-Yates, L. Dempere-Marco, H. Saggion, Frequent Words Improve Readability and Short Words Improve Understandability for People with Dyslexia, 8120 (2013) 203–219.

[34] S.O. Richardson, The Montessori Preschool: Preparation for Writing and Reading, Ann. Dyslexia. 47 (1997) 241–256.

[35] E. Schneider, T. Evers, Linguistic Intervention Techniques for At-Risk English Language Learners, Foreign Lang. Ann. 42 (2009) 55–76.

[36] M.J. Snowling, J. Stackhouse, Dyslexia, Speech and Language: A Practitioner's Handbook, John Wiley & Sons, 2013.

[37] J.-Y. Sung, A. Levisohn, J. Song, B. Tomassetti, A. Mazalek, Shadow Box: an interactive learning toy for children, in: First IEEE Int. Workshop Digit. Game Intell. Toy Enhanc. Learn. 2007 DIGITEL 07, 2007: pp. 206–208.

[38] C. Sylla, C. Coutinho, P. Branco, W. Müller, Investigating the use of digital manipulatives for storytelling in pre-school, Int. J. Child-Comput. Interact. 6 (2015) 39–48.

[39] C. Sylla, I.S.P. Pereira, C.P. Coutinho, P. Branco, Digital Manipulatives as Scaffolds for Preschoolers' Language Development, IEEE Trans. Emerg. Top. Comput. 4 (2016) 439–449.

[40] Y.E. Tang, Self-reported strategy use while reading in English and Mandarin: A study of four ESL students, 2002.

[41] F.R. Vellutino, J.M. Fletcher, M.J. Snowling, D.M. Scanlon, Specific reading disability (dyslexia): what have we learned in the past four decades?, J. Child Psychol. Psychiatry. 45 (2004) 2–40.

[42] K.S. Vickery, V.A. Reynolds, S.W. Cochran, Multisensory teaching approach for reading, spelling, and handwriting, Orton-Gillingham based curriculum, in a public school setting, Ann. Dyslexia. 37 (1987) 189–200.

[43] M. Wang, E. Geva, Spelling acquisition of novel English phonemes in Chinese children, Read. Writ. 16 (2003) 325–348.

[44] R. Wang, 甘肃省农村小学英语教学的现状、问题与对策研究 [Primary school English teaching in Gansu province: Current status, problems and solutions], 西北成人教育学报. 1 (2009) 73–75.

[45] M. Wrembel, Sound symbolism in foreign language phonological acquisition, Res. Lang. 8 (2010) 1–14.

[46] S.H.M. Yeong, S.J. Rickard Liow, Development of phonological awareness in English–Mandarin bilinguals: A comparison of English–L1 and Mandarin–L1 kindergarten children, J. Exp. Child Psychol. 112 (2012) 111–126.

[47] L. Yin, Stages in Chinese children's reading of English words, Ph.D., University of Illinois at Urbana-Champaign, 2005.

[48] L. Yin, R.C. Anderson, J. Zhu, Stages in Chinese children's reading of English words., J. Educ. Psychol. 99 (2007) 852.

[49] R.K. Yin, Case study research: design and methods, Fifth edition, SAGE, Los Angeles, 2014.

[50] D. Zhang, Chinese primary school English curriculum reform, in: Perspect. Teach. Learn. Engl. Lit. China, Springer, 2012: pp. 67–83.

[51] J.C. Ziegler, U. Goswami, Reading Acquisition, Developmental Dyslexia, and Skilled Reading Across Languages: A Psycholinguistic Grain Size Theory, Psychol. Bull. 131 (2005) 3–29.

Appendix A

Trained words (Pre-test, instruction, & post-test)	**Untrained words (Pre-test and post-test)**
Session 1 (CVC_1)	
bet (s)	pet (s)
dad	had
tin	win
Session 2 (CVC_2)	
pup	cup
hit *	sit *
web	deb
Session 3 (Consonant blends)	
flag	flat
crab	crag
stop *	step *
Session 4 (Consonant digraph)	
thin	thug
shop *	ship *
chip	chop
Session 5 (Magic e rule_1)	
game *	name *
tape	cape
cake	lake
Session 6 (Magic e rule_2)	
side	hide
wide	tide
late	date
Session 7 (Vowel team)	
eat *	tea *
boat	toad
paid	raid
Session 8 (Syllable division)	
over *	under *
water	river
creepy	sleepy
The word with * was for the spelling task.	

Research highlights

- Ten EFL children achieved significant learning gains after PhonoBlocks instruction.
- Dynamic colours in 3D tangible letters draw attention to how letters change sounds.
- 3D tangible letters enable correct letter orientation and epistemic strategies.