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Why Tangibility Matters: A Design Case Study of At-Risk Children Learning to Read and Spell

Min Fan[1] **Alissa N. Antle**[1] **Maureen Hoskyn**[2] **Carman Neustaedter**[1] **Emily S. Cramer**[1]
School of Interactive Arts & Technology[1]
Simon Fraser University
250-13450 102 Avenue
Surrey, B.C. Canada V3T 0A3
Centre for Research on Early Child Health and Education[2]
Simon Fraser University
8888 University Drive
Burnaby, B.C. Canada V5A 1S6
[minf, aantle, mhoskyn, carman, ecramer]@sfu.ca

ABSTRACT

Tangibles may be effective for reading applications. Letters can be represented as 3D physical objects. Words are spatially organized collections of letters. We explore how tangibility impacts reading and spelling acquisition for young Anglophone children who have dyslexia. We describe our theory-based design rationale and present a mixed-methods case study of eight children using our PhonoBlocks system. All children made significant gains in reading and spelling on trained and untrained (new) words, and could apply all spelling rules a month later. We discuss the design features of our system that contributed to effective learning processes, resulting in successful learning outcomes: dynamic colour cues embedded in 3D letters, which can draw attention to how letter(s) position changes their sounds; and the form of 3D tangible letters, which can enforce correct letter orientation and enable epistemic strategies in letter organization that simplify spelling tasks. We conclude with design guidelines for tangible reading systems.

Author Keywords

Tangible user interfaces; dyslexia; children; embedded interaction; reading acquisition; mixed-methods.

ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces. K.3.2. Computers and education: Miscellaneous.

INTRODUCTION

Success in early reading acquisition requires learning phonological awareness (PA), which is the ability to identify and manipulate units of oral language (e.g. the sounds that groups of letters make) and learning the alphabetic principle, which is that letters represent sounds which form words according to predictable relationships or rules that link letters and spoken sounds. If a child understands these kinds of letter-sound associations then s/he will be able to learn to read and spell words [6,26,30]. However, in English-speaking countries, approximately 10% of children have difficulties in learning to read and spell [17]. This specific learning difficulty is referred to as "dyslexia" [26]. Dyslexia can result in tremendous social, emotional and economical costs for children, their families and society. Recent research has suggested the potential of tangible user interfaces (TUIs) in supporting learning to read for children, particularly for children with dyslexia [9,13]. Despite these suggestions, few TUIs have been designed for children with dyslexia (for exceptions, see [23,24]). Few empirical studies have evaluated if, and how such systems support children in learning to read (for an exception, see [13]). No systems have been designed that explicitly address and evaluate early reading acquisition targeting PA and the alphabetic principle.

We address this opportunity and knowledge gap by presenting the theory-based design and evaluation of a tangible reading system called PhonoBlocks. Our goal was to create a system to help 7 to 8 year old children at risk for dyslexia to learn six letter-sound rules required to read and spell many words in English, which they had been unable to learn with classroom instruction. We targeted PA and the alphabetic principle as critical phases in early reading because children with dyslexia struggle with these concepts, which all children must master. The design of PhonoBlocks, in particular its two core design features, dynamic embedded colour cues and 3D tangible letters, were developed based on theories of causes of dyslexia and analysis of non-computational multi-sensory reading interventions, which are effective but resource intensive. We used a mixed-methods approach to investigate *if* and *how* our system might help Anglophone children at risk for dyslexia to learn to read and spell a set of English alphabetic rules.

In this paper, we present an analysis of eight individual cases who each received a total of 12 x 20 minute training sessions with PhonoBlocks. We provide a summary of quantitative results of children's reading and spelling gains, and then provide a detailed analysis of the qualities of interactions and behaviours that PhonoBlocks enabled in order to better understand how tangible design elements may facilitate learning to read and spell. Our results provide empirical

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evidence that indicates two unique features of tangibility were effective in supporting children at risk to learn to read and spell. Our results may be generalizable to TUI systems designed to support second (foreign) language learners who face similar challenges to the students in our study, and because all children must learn PA and the alphabetic principle, to TUI early reading systems for typical children.

BACKGROUND

Theories of Dyslexia

Dyslexia is a specific learning difficulty that affects children's language acquisition skills such as learning to read and spell. Although dyslexia is heterogeneous, the most direct cause is suggested to be impairment in phonological awareness, the ability to hear sounds that make up words in spoken language. This includes recognizing when words rhyme, judging if words begin or end with the same sounds and understanding that sounds can be manipulated to create words [26,30]. Phonological deficits impede children's acquisitions of the alphabetic principle and the subsequent mastery of language. In addition, dyslexia often co-occurs with attentional deficits [25]. Learning to read English poses particular challenges for children with dyslexia due to its inconsistent letter-sound mappings in its orthography (referred to as an "opaque" language) [6,28]. Therefore, helping children with dyslexia to improve their phonological awareness and cueing attention to the alphabetic principle are extremely important during the acquisition of "opaque" languages.

Multisensory Instruction

Although dyslexia is a lifelong condition, children with dyslexia can learn to read and spell under proper instruction [6]. Research suggests that explicit, intense, and highly structured phonics-based instruction, which stresses the acquisition of the alphabetic principle and its use in reading and spelling, has been effective, particularly for children with dyslexia [15,26]. Phonics-based training also helps children learn PA because it focuses on the reciprocal relationship between PA (focus on sounds) and the alphabetic principle (focus on letters) [18]. One widely used phonics-based approach is the multisensory approach in which visual, auditory, tactile, and kinaesthetic representations are linked to help children understand letter-sound associations [15]. Other approaches, like the Montessori method, which may use multi-sensory materials, have produced inconsistent results and remain under-studied.

The Orton-Gillingham (O-G) program is one example of multisensory instruction [27]. The O-G program is often conducted with a trained tutor supporting a child with dyslexia [15]. The tutor directs the activity and uses a phonics-based approach to explicitly teach the child letter-sound correspondences using multiple forms of representations [15]. For example, physical letter tiles or coloured beads, which may be put into sequences, are often used in the O-G program [3]. One important sensory activity in the O-G program is having children trace letters to develop an understanding of how they feel [3]. Like typical readers, dyslexic children also have problems distinguishing mirrored letterforms [6]. The letter tracing activity can help dyslexic children to learn similar letterforms [3,6]. Handling letters while sounds are played may improve dyslexic children's attention to letter-sound correspondences [10,20] as well as helping them learn, remember and apply spelling rules [2]. During such interventions, tutors may also use other cues such as pictures [8] and colours (e.g. *pat*, *rat*, *bat*) [4,14] to attract children's attention to and improve memory of letter-sound correspondences. However, one limitation of this approach is that it is extremely resource intensive. Most O-G programs do not involve computational materials and rely on highly trained tutors who provide many one-to-one sessions with structured guidance and feedback.

Tangible Reading Systems for At-Risk Children

Researchers have highlighted the potential of computer-based methods for reading instruction. Some potential advantages are: cost-effectiveness [9,22]; digital feedback; playful learning through multimedia (e.g. text, images, sounds, and objects); and motivational game-mechanisms [21]. Compared to graphic user interfaces (GUIs), the physical and spatial qualities of TUIs may be beneficial because the letters can be represented as tangible objects that can be interacted with more easily than printing letters, can be traced, and are easily organized into related groups and/or linear sequences of words. There are many tangible reading prototypes (e.g. [7,11,16,29]) and several commercial products (Tiggly[1], Osmo[2]). Few are specifically designed for children with reading difficulties and most focus on a whole-word approach which is ineffective for children struggling with PA and the alphabetic principle [6]. Therefore, tangible reading systems designed for typical children, particularly those focusing on the whole-word approach, are likely to be ineffective for children at risk for dyslexia.

We identified two systems specifically designed for children with dyslexia [23,24] and one designed for non- or hardly speaking toddlers [13]. SpellBound is a tangible system that supports dyslexic children to learn letter-sound correspondences [23]. SpellBound allows children to construct 2D letters by using a set of flat wooden shapes that can be used to form letters (e.g. the crossbar of a *t*, or tail of a *q*). Then, each 2D letter can be placed onto a platform to trigger the letter sound and associated 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 complex rules of letter-sound correspondences in words.

Tiblo uses Lego-like blocks to represent words, numbers, or phonemes, which are distinct sounds (e.g. *a, th, ex*) [24]. Children with dyslexia can draw the concept on a piece of

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[1] https://www.tiggly.com

[2] https://www.playosmo.com

paper, attach it to a block, and record the sound for the concept. A set of blocks can then be connected in a certain order to represent a word, narrative or any other concepts. Apparently, the typical user scenario of Tiblo is not the acquisition of letter-sound correspondences. Furthermore, the researchers only evaluated the usability of this prototype but not its effectiveness in supporting children learning to read.

Hengeveld and colleagues developed LinguaBytes, a tangible system aimed at stimulating language development for non- or hardly speaking toddlers aged 1-4 years [12,13]. LinguaBytes consists of a digital display, a physical control panel, and a wide range of tangible input materials such as story booklets, 3D tangible letters, and programmable RFID labels. This prototype can support a variety of activities including exercises related to phonological awareness, semantics, and story reading. In the phonological activity, toddlers learn letter sounds by placing one 3D tangible letter on the platform. Audiovisual feedback is provided on the digital display, including 2D words and sounds starting with the same letter. The 3D tangible letters of LinguaBytes enable letter tracing and organization of letters in space. The coupling between the 2D word and sound on the display and the 3D tangible letter enables toddlers to learn letter-sound correspondences by using multiple senses. However, the design of LinguaBytes is limited in only allowing toddlers to learn basic one-to-one letter and sound associations rather than the rules of often inconsistent letter-sound mappings in words. The researchers used a research-through-design approach to iteratively design and evaluate the prototype. They argued that tangible interaction offers more opportunities for collaboration between the therapist and the child and promotes engagement that can consequently lead to more opportunities for learning.

In summary, previous research has suggested that TUIs may have the potential to help children to learn to read and spell. However, current tangible reading systems do not focus on helping children at risk for dyslexia learn PA or the alphabetic principle. Nor do they fully leverage the use of TUI features suggested by multisensory instruction (e.g. 3D tangible letters, dynamic colour cues). Lastly, few empirical studies have evaluated if and how such systems support children learning to read. We address all three of these knowledge gaps in our work.

SYSTEM DESCRIPTION

The theories of the causes of dyslexia and best practices of multisensory instruction suggest that the system should satisfy the following key requirements:

- The phonological deficit theory of dyslexia [26,30] and the opaque orthography of English [6,28] suggest that the learning goal should focus on letter-sound correspondences within word contexts (***Req1***).
- The phonological deficit theory [26], attentional challenges [25] and successful multisensory interventions [15] suggest the potential of using multiple cues such as colour [4,14] and pictures [8] to help children notice the common patterns within words while learning of letter-sound correspondences (***Req2)***.
- Multisensory interventions suggest the importance of the tutor's role during the learning process [15] (***Req3***), although we would like the children to also be able to practice on their own with feedback to reduce resources.
- The importance of letter-tracing [3] and manipulation [2,10,20] suggests the inclusion of letterforms in the design of physical representations in TUIs (***Req4***).

Based on these four requirements, we present the design of a tangible reading system called PhonoBlocks designed for 7 to 8 year old children at risk for dyslexia to support their learning of six rules that are part of the alphabetic principle in English (***Req1***). PhonoBlocks is comprised of a touch-based laptop display, a word-making platform with seven slots, and 46 lowercase "hand-sized" 3D tangible letters (duplicates for common letters, e.g. *a, e, d, t*) (***Req4***). 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 (***Req2***) (e.g. Figure 1). Visual and audio feedback are also provided on the digital display using coloured 2D letters and playing associated letter sounds (***Req2***).

PhonoBlocks contains the following basic features (1) displays a picture related to the word meaning so that children can use pictorial cues to consolidate their memory of letter-sound correspondences (***Req2***) [8]; (2) provides a both tutor and child modes, which offers the freedom for tutors to teach each activity and/or allow a child to practice on their own through a set of games (***Req3***)[15,21]; (3) offers a word history list that displays all words made so far, so that children can compare new and previous words (and see their progress) (***Req3***) [15]; and (4) incorporates a function that enables children to blend letters into a whole word by swiping right across the word to trigger the whole word sound and display letters in a single colour (purple) or decode a word into individual letters and sounds by swiping left across the word to display separate letter colours and clicking a button to trigger individual letter sounds. This function enables children to practice blending and decoding skills (***Req1***) [30].

In addition to the general features, PhonoBlocks has two novel design features: embedded dynamic colour and 3D tangible letters.

Figure 1. Magic-e activity: the colour of "*a*" changes from yellow to red to illustrate the sound change from short to long.

Embedded Dynamic Colour Cues

We use dynamic colour embedded in the 3D letters to cue (attract) children’s attention to the moment when adding new letter(s) changes sound(s) and, in doing so, *explicitly* show them the letter-sound correspondences in different word contexts (***Req1&2***). Each of the six rules has a unique dynamic colour cue design. For example, in the consonant blends activity, the letter *f* and letter *l* change to green to indicate they make a blended sound together. In the magic-e activity, the vowel letter changes from yellow to red to indicate the vowel sound changes from short to long when a trailing *e* is added (Figure 1). We also use flashing colours to draw attention to changes. For example, in the magic-e lesson, when the vowel is placed, the letter flashes three times before staying yellow (short sound). After an *e* is added, both the *e* letter and the vowel letter flash three times, then change to red together. The specific dynamic colour cue design for each rule can be found in Table 1.

3D Tangible Letters

We use sturdy, hand-sized 3D tangible letterforms to facilitate letter tracing and manipulation activities ***(Req4)***. We use physical constraints: a notch in each letter, to help children learn the orientation of mirrored letters (e.g. *p*, *d* or *b* can only be placed correctly due to the physical notch constraint). Embedded colours are only displayed when letters are placed on the platform; on a table letters are offline, encouraging manipulation.

Learning Activities: Six Spelling Rules	Examples
1. **Consonant Vowel Consonant (CVC)**: CVC patterns	bet pet jet
2. **Consonant Blends:** two consonants make a blended sound in which you can hear two parts to the sound	f → fl → flag
3. **Consonant Digraphs:** two consonants make one sound	t → th → thin
4. **Magic-e Rule**: vowel sound changes from short to long when an *e* is added at the end of word	gam → game
5. **Vowel Teams**: two vowels make one sound	e → ea → eat
6. **R-Controlled Vowels**: r-controlled vowel sounds in which different vowel-r combinations sound the same	er → stern ur → turn

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

STUDY METHODOLOGY

The overarching goal of this study was to explore the effectiveness of PhonoBlocks, and to evaluate how design features impacted learning. Our research questions are:

- ***RQ1***: *Do children improve word reading and spelling accuracy after instruction with PhonoBlocks on trained words, new words, and on both after a month?*
- ***RQ2***: *What are the key design factors in PhonoBlocks that benefit children in learning to read and spell?*
- ***RQ3***: *What do children like and dislike about the system?*
- ***RQ4***: *Do children’s individual characteristics influence learning performance, behaviours, and/or likes/dislikes?*

We used a case study design to address these research questions for two main reasons: (1) it is critical to evaluate the system in the real life context. It is not feasible to find two “matched” groups of children at risk for dyslexia in a school context due to the variety of children’s backgrounds and learning challenges; (2) understanding the relationship between children’s learning performance (reading and spelling scores on pre-, post- and follow-up tests), interactional behaviours with the system, preferences and individual characteristics (e.g. attentional challenges, motivation, temperament) requires mixed data sources and detailed examination of evidence, an approach supported in case-by-case analysis. We also interviewed teachers about each child’s challenges and any changes they noticed over the course of our study.

Participants

The resource teacher recruited eight children, 7-8 years old, studying at a public elementary school in an urban city in Canada to participate in our study. The teacher identified them as at risk for dyslexia. There were five boys and three girls with an average age of 7.3±0.5 years old. We assessed each child’s current knowledge of English to ensure they knew letter names and basic sounds but had minimal knowledge of how to read and spell words using our six rules.

Tasks

The learning tasks were six rule-based lessons, including: Consonant-Vowel-Consonant (CVC), Consonant Blends, Consonant Digraphs, Magic-e Rule, Vowel Teams, and R-Controlled Vowels lessons (Table 1). Children learned each of the six rules in two x 20 minute individual sessions, for a total of 12 sessions. We developed the lesson plans and word lists based on previous research [4] and following suggestions of an educational psychologist and the school’s resource teacher who specialize in teaching children with dyslexia. We chose these rules because they are appropriate for 7 to 8 year old children and teachers often spend hours/weeks teaching them. We also verified that the words and rules used in our study were not being taught in class during the time of our study. Children worked with the facilitator to learn three words in each session (e.g. *bet, dad, tin*, called the “trained words”), for a total of 36 trained words over 12 sessions. In addition, children practiced the rule by themselves by building three new *variation* words, (e.g. *dad-bad, tin-bin, bed-ted*).

In order to examine whether the children remembered trained words, we tested their reading and spelling accuracies on 36 trained words for reading and 12 trained words for spelling. In order to examine if they could transfer the rules to other similar words we tested 36 (new) untrained words for reading and 12 untrained words for spelling that followed the same rules in a post-test. In order to examine if children could remember the rules and apply them in other contexts we examined “maintenance” by conducting a follow-up test on trained and untrained words one month after the post-test.

Procedure

Prior to using PhonoBlocks the children received a pre-test for baseline assessment (see details under Data Collection and Analysis below). All tests were individually administered by a research facilitator in a quiet room at the school, taking 30 minutes for each child. Then each child was taken out of class three times a week to receive the 12 one-to-one training sessions facilitated by a single trained research facilitator in a quiet room at the school. The facilitator was trained by the educational psychologist and they then co-developed the teaching protocol. Each session lasted about 30 minutes, including 15 minutes of instruction with the facilitator, five minutes of the child practicing with the system, five minutes for a reading test (not reported in this paper), and five minutes for transition. During instruction, the facilitator used a teaching protocol that followed an explicit phonics-based approach to teaching the letter-sound associations [4]. The facilitator was allowed to answer the participants' questions, re-direct their attention, and provide help when the children were stuck during instruction. However, during practice time, the children had to complete the spelling tasks for new words using the system by themselves. The facilitator only provided technical support if needed (e.g. making sure a letter was clicked into its slot).

The post-tests were conducted immediately after all the sessions. Each child's word reading and spelling accuracies were assessed individually by the facilitator. The entire post-test assessment took approximately 30 minutes for each child and was conducted over two days. After the post-test, each child was individually asked a set of closed (Likert-scale) and open questions pertaining to their preferences about the system. The facilitator read the questions and wrote down the answers (since the children cannot read or write reliably). The teachers of the children were also interviewed about the challenges for each child (e.g. attentional, learning, social, emotional), other characteristics (e.g. temperament, visual-spatial skills, motivation, curiosity, competitiveness) and whether they had seen any change over the one month study. The follow-up maintenance test was conducted one month after the post-test. The procedure was similar to that of the post-test.

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 36 words they were going to learn. The words were presented on a computer screen. They were asked to spell 12 words they were going to learn on paper. The raw accuracy scores for reading and spelling were recorded (e.g. 8/36, 3/12). During the post- and maintenance tests, the participants were asked to read the same 36 (now trained) and 36 (new) untrained words presented on a computer screen and to spell 12 trained and 12 untrained words on paper. The accuracy scores were recorded. Children and teachers were asked open and closed questions after all the sessions (as above).

After the sessions children were asked to rate their preferences on a variety of questions. They were asked to rate how much they liked/disliked the system, how easy the system was to use, how much they would like to continue using the system and how much they liked the dynamic colour cues and 3D tangible letters. We used a 4-point scale suitable for young children, including *Not at all, A little, Some* and *Very much*. We assigned a value 1 (*Not at all*) to 4 (*Very much*). We also asked teachers about children's challenges (learning, attention), skills (visual-spatial), and temperament (extroverted, curious).

We also collected data about the children's interactional behaviours using video recording and structured observational note sheets. Notes were taken by the facilitator and a second researcher who operated the video camera and helped with transitions.

We used quantitative methods to address ***RQ1** (effective)*, including using correlated *t*-tests to determine the differences of the means of the raw scores[3] of reading and spelling accuracies on trained and untrained words between the pre and post, and post and follow-up tests. We conducted participant level analysis to ensure that individuals did not unduly account for affects. We used thematic analysis to address ***RQ2** (design elements)*, including identifying common and interesting patterns of interaction from the video and from observational notes. We used both quantitative and qualitative methods to address ***RQ3** (preference)*, including analyzing 4-point Likert scales questions (e.g. How much did you like using the system?) with descriptive statistics and analyzing children's responses to the open-ended questions looking for interesting and common themes. We also used both quantitative and qualitative methods to address ***RQ4** (individual characteristics)*. We first re-coded data about individual characteristics to binary (e.g. attention issues) or ordinal (e.g. introvert/mixed/extrovert to -1, 0, 1), and ran the appropriate correlational tests between children's learning gains, preferences and individual characteristics. We also supplemented these findings with observations and teacher interviews. One child (P7) was absent for a prolonged period and so we could not administer the maintenance test.

RESULTS

Reading and Spelling Accuracy

For *reading*, correlated *t*-test results showed that there was a statistically significant increase at the $p<0.01$ level in participants' raw accuracy scores on trained word reading accuracy between the pre- and post- tests, increasing from 19.4±9.6 words to 34.9±0.8 words out of 36 trained words in total ($t(7)=4.808, p=0.002, d=1.7$). The participants transferred some of their new reading knowledge to the untrained words. Results showed that there was a statistically significant increase at the $p<0.01$ level in participants' scores

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[3] Raw scores = each word was scored 1 score for a correct word and 0 score for an incorrect word.

between the pre-test trained words and the post-test (new) untrained words (*t*(7)=4.335, *p*=0.003, *d*=1.5). The mean of children's scores increased from 19.4±9.6 to 33.1±1.6 words out of 36 trained/untrained words. There was a statistically significant difference at the *p*<0.01 level on the post-test reading improvement between the trained and untrained words (*t*(7)=4.249, *p*=0.004, *d*=1.5).

For *spelling*, results showed a statistically significant increase at the *p*<0.01 level in participants' scores on trained word spelling between the pre- and post-tests, increasing from 5.8±3.1 to 10.0±1.9 words out of 12 trained words (*t*(7)=4.937, *p*=0.002, *d*=1.8). The participants transferred some of their new spelling knowledge to the untrained words. Results showed a statistically significant increase at the *p*<0.01 level in participants' scores between the pre-test trained words and the post-test (new) untrained words (*t*(7)=3.851, *p*=0.006, *d*=1.4). The mean of raw scores increased from 5.8±3.1 to 8.9±2.0 words out of 12 trained/untrained words. Results also showed a statistically significant difference at the *p*<0.05 level on the post-test spelling improvement between the trained and untrained words (*t*(7)=2.826, *p*=0.026, *d*=1.0).

For *reading accuracy maintenance* results showed no statistically significant difference between participants' raw scores on trained word reading accuracy (*t*(6)=0.281, *p*=0.788*)* and on untrained word reading accuracy (*t*(6)=1.179, *p*=0.283) between the post- and follow-up test. Participants (without P7) maintained both trained and untrained word reading after one month. For *spelling accuracy maintenance* results showed no statistically significant difference of participants' raw scores on trained word spelling accuracy (*t*(6)<.0001, *p*>.99) and on untrained word reading accuracy test (*t*(6)=1.508, *p*=0.182) between the post-test and follow-up tests. Participants (without P7) maintained the observed effects of trained word spelling after one month.

In summary, our instruction with PhonoBlocks was effective in helping participants to learn 6 rules (from the alphabetic principle) used in reading and spelling, and took about 20 minutes per rule, which is significantly less resource intensive than approaches used by the tutors we interviewed.

Beneficial Design Features

Dynamic Colour Cues Embedded in Tangible Letters

Most participants were attracted to and engaged with the flashing dynamic colour cues. We saw this when children (1) asked questions about the meaning of the colours; (2) wanted to try out other words to see if the colours would stay or change; (3) asked about what colours would appear in new lessons; and/or (4) made comments about the colour cues after the colour change flashed. For example, when P1 first used the blend/decode function, he was very excited and asked: "Now it's all purple! Why it's all purple?" In the consonant diagraph session, P6 wanted to know what would happen if he switched the two consonant letters in the consonant digraph *sh*: "I am wondering what will happen if I switch them (*sh*) around. Is it still green?" P6 often asked how the dynamic colour cue would work in the next session: "What's the colour for the magic-e?" or made comments about it "I like purple!" "You should change this (the blended colour) to blue." "It's cool!" These verbalizations indicated that children's attention and interest was drawn to the dynamic colour cues.

The participants were able to understand or quickly learn what the dynamic colour cues represented. For example, in the r-controlled vowel lesson, when making the word *car* P8 saw that the *ar* pair changed red together. She guessed and said: "The red colour means they (the *a* and *r* letters) go together," even before the facilitator explained the meaning of the colour. She automatically focused on the red *ar* pair rather than the letter *c* (which was in white).

We also asked whether children understood what colour changes meant. For example, in the consonant blends lesson, when the facilitator asked: "How come it (*st*) was supposed to be green?" P1 answered: "They make a blended sound." In response to same question, P2 said: "Because it's supposed to be blended together." In the consonant digraphs activity, P3 and P7 said green letters meant the two letters were working together. In the magic-e activity when the facilitator asked: "What does the red mean?" P2 said: "The magic *e* makes the (vowel) letter to say its name (pointing to the vowel letter)." The facilitator said: "If I take out the letter *e*, what colour will *a* be?" P2 said: "yellow".

Some children noticed patterns of colour change without being asked by the facilitator. For the magic-e rule P1, P5, and P6 all spontaneously described the colour change when the trailing *e* was added. P5 said: "Oh, it's a pattern, blue (blue-ish-white), red, blue, red." P6 pointed at each letter and said: "…white, red, white, red.". Similarly, in the r-controlled vowel lesson, even before the facilitator explained the colour change, when P8 saw the *ar* change to red when making the word *car*, she said "The red colour means they (the *a* and *r* letters) are together." These verbalizations provide evidence that most children understood how the letter colours and sounds changed for each rule.

The colour flash is also important because it draws attention to the moment when placing a letter(s) changes a sound (s). For example, we observed that the yellow and red vowel flashes encouraged the children to notice the vowel sound changes from short to long when an *e* was added in the magic-e rule.

The participants noticed "unexpected" changes in colours and used them to detect spelling errors. In the magic-e activity, P2 misspelled the word *late* as *latb*. She noticed that the expected colour change pattern did not happen (white-red-white-red). She tried placing the same letters again, realized her mistake and changed the letter from *b* to *e*. When asked how she knew she had made a mistake, she explained: "Because it (the vowel letter) wasn't turning red." In the vowel teams lesson, when the facilitator asked P1 to make the word *heat*, P1 placed the letters *ie* and said: "They are not red." He then changed the vowel letters to the correct ones (*ea*), which turned to red.

3D Tangible Letters

The participants used the physical constraints (notch) to determine correct letter orientation. For example, many participants (P2, P3, P6, P7, and P8) looked at the bottom of the tangible letters where the notch was to determine the correct orientation of the letters. The participants also realized that the orientation mattered for some letters more than others. For example, P6 said: "The *o* can be put in this way or that way." In the CVC lesson, P4 was asked to make the word *bad*. He picked up the letter *d* and placed it onto the first slot on the platform. He then stared at the letter *d* and said to himself "Is it the other way around?" After thinking for a while, he switched the orientation but found it did not match to the opening for the notch in the slot. Eventually, he put *d* down and picked up the letter *b* and put it onto the first slot of the platform correctly.

The participants compared mirror letter shapes side-by-side to determine correct letter orientation. Several participants (P2, P6, and P8) made comparisons by physically holding the two similar tangible letters side-by-side when making the words that contained the mirrored letters *b*/*d* (Figure 2). For example, in the CVC lesson, when the facilitator asked P2 to make the word *bad*, P2 was not sure about *b/d*, so she held the letter *d* in her hand and compared it with the other letter *b* on the platform. After she had confirmed that the letter in her hand was *d*, she placed it onto the platform. The 3D tangible letter forms enable children to easily compare mirrored letter shapes by seeing, touching or even tracing these letters. Comparing and rotating physical letters is a form of complementary action which may simplify the task by shifting a mental task to a visual-physical task (i.e., cognitive offloading) [1]. This strategy may explain why many participants' spelling accuracy on words with *b/d* letters on paper were worse in the post- and follow-up tests compared to that during practice with the system. Practicing spelling with 3D tangible letters enables strategies that simplify determining the correct orientation of mirrored letters. This may help a child attend to the rules of spelling rather than focusing on writing a letter in the correct orientation.

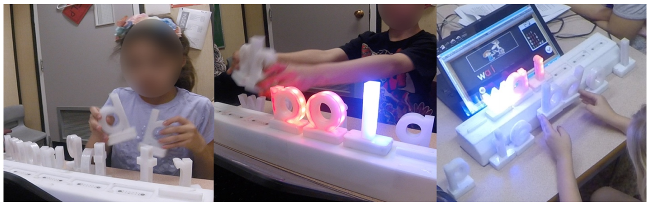

Figure 2. P2, P6, and P8 compared *b* and *d* letters.

Many participants developed spatial organization strategies to simplify spelling tasks. Children used space to organize the physical letters in three ways. First, some participants (P1, P4, P5, P6) placed the tangible letters in a line, which appeared to help them visually and physically find certain letters. P1, P4, and P5 often lined them up in alphabetic order so they could quickly find the letters they needed.

Second, several participants (P4, P5, P8) picked up tangible letters they were going to use later and held all of them or placed them aside in a group (Figure 3). For example, when making the word *trip*, P5 first picked up all four letters, held them in his hands, and then placed them one by one onto the platform. When building the word *bet*, P8 first selected all the letters she needed to use, placed them in front of her, and then put them onto the platform. Similarly, P4 and P8 often picked up letters and placed them on the desk first. P5 often held letters in her hands before placement.

Third, P8 developed strategies to manage the letters differently for each learning activity. In the CVC activity, she placed all the vowel letters to one side. In the vowel teams activity, she placed all the vowel letters on the right side and all the consonant letters on the left side. In the r-controlled vowel lesson she changed her strategy and put all the vowel letters *a*, *u* and *o* together followed by the letter *r* (Figure 4). Our design enabled children to organize tangible letters on the desk space to make their tasks easier to solve later (called epistemic actions [1]).

Figure 3. P5 held the letters in *flop* in his hands (*left*); P8 placed the letters for *bet* grouped in front of her (*right*).

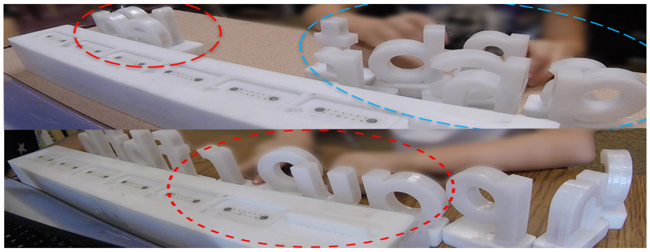

Figure 4. Vowel teams rule: vowel letters on the right side and consonant letters on the left side (*top*); r-controlled vowel rule: all the vowel letters together with followed by *r* letter (*bottom*).

Participants' hand actions mirrored their understanding of how letters make sounds. We noticed that some participants placed letters one by one when they were learning a rule, but then later placed pairs of letters with two hands (e.g. for blends) once they understood the rule. Most participants (P2, P4, P5, P6, and P8) switched from this kind of one- to two-handed interaction as they learned rules. For example, when P4 was asked to make the word *chin*, he first placed the letter *h* in the second slot, thought for a while, and then placed the letter *t* in the first slot (*th* not *ch*). This suggested that he was confused about the *ch* and the *th* sounds and used a single hand to place each letter of the consonant digraph. However, when he made the *sh* pair in the word *shop*, he picked up the letters *s* and *h* simultaneously using two hands, showing his understanding of their blended sound. We noticed this pattern frequently with P2, P4, P5, P6 and P8 when they were making words that contained consonant blends, consonant digraphs, vowel teams, and r-controlled vowel pairs.

We also noticed that the participants (P4, P5, and P8) sometimes crossed their hands to place the tangible letter pairs when they were extremely sure about their answers (Figure 5). For example, P4's verbalizations show that he quickly remembered the *sh* pair. For example, P4 said, "I can memorize the word *shop,* I need *s* and *h.*"). In this case, since the letters were on the desk in reverse order, P4 picked them up by crossing his arms-hands to put the letters into the correct order to make *sh* in the word *shot*. P5 did the same thing to make the *ea* pair for the word *beat.* P8 also used this crossed action when making the *oa* pair for the word *coat*. It seems that as children become more certain of the rules, they take a shortcut, moving letters into the correct order as they move them through the air into place, rather than organizing them first on the desk space and then moving them in slots.

Figure 5. Shortcut: Ordering letters in the air on route to placing them: consonant digraph (*sh*) & vowel teams (*ea*, *oa*).

Other Important Design Features

The pictures associated with words aroused the participants' interest in learning with the system and may have promoted associative learning. The video and observational data showed that the participants always checked the picture for each word. They smiled or made comments about the pictures. For example, P8 smiled when she saw the picture of the word *pup* and said: "It's so cute!" The pictures also allowed the participants to associate different but related words with the one depicted in the picture. For example, When P1 saw the picture of the word *jar*, he said: "It's jelly jar! Delicious!" "Both the words *jelly* and *jar* start with the same letter *j*."

The participants enjoyed playing on their own in practice mode. For example, during the instruction, P1 always asked "Can I do the challenges (practice mode) now?" P6: "When can I play the game?" Our video data also showed that the participants were excited to hear the rewarding sounds and pictures when successfully completing the tasks. P1 showed the victory gesture and said "Yeah!" when he correctly completed the spelling tasks. P3, P6, and P8 smiled when they heard the rewarding sounds.

Many participants (P1, P3, P4, P5, P7, and P8) often used the word history list. The word history list contained all the words children had made. They could touch a word to trigger its sound or visually compare common patterns between the words. For example, when making the new vowel team words (*beat* and *load*), P4 and P5 checked the words they already had in the word history list (*eat, boat*) and compared the common vowel team patterns.

The blend/decode function was frequently used during the instruction and practice parts of sessions. We observed that all the participants clicked the button to listen to the individual letter sounds (letters are coloured based on their sounds) and the blended word sound (when letters are coloured all purple). When the letters were all purple in the blending mode the children tended to focus on the whole word by sounding out the whole word. However, when the letters were in various colours in the decoding mode, the children tended to focus on the different coloured parts by sounding out the individual phonemes. We observed that P1, P3, P4, P6, P7, and P8 often used this function after they created a word - they listened to the blended sound of the whole word when the colours changed to purple. They then clicked the button again to hear the individual letter sounds and to see the colours change back. After instruction in the tutor mode, most of the participants practiced the blend/decode function on their own. We could see them attend to the whole word and individual letter sounds when using this function. Some participants (P2, P4, P7, and P8) also used this function to check if they had spelled a word correctly before submitting it. When P2, P7, and P8 expressed doubt about their spelling they often clicked the button to check the individual sounds before submitting their answers to the system.

Children's Preferences

The results of the preference ratings (1-4 scale) showed that most participants really liked the system (mean=3.8±0.7), thought the system was easy to use (mean=3.8±0.5) and said they would like to continue using the system (mean=2.9±1.4). We interpret this cautiously due to the novelty effect and researcher-child power difference. We asked children who said they did not want to continue for their reasons. P8 said she did not want to miss gym time. P1 did not give a reason. However, we observed that he often looked engaged in the class he was in at session time, and was often resistant to leaving that class. We infer that sometimes when children were taken out of classes they enjoyed it reduced their motivation to use our system, which in turn may have impacted learning, but could be overcome when our system is used in a normal (non-research study) classroom context.

The participants were also asked how much they liked the dynamic colour cue feature. The results showed that all participants really liked this feature (mean=4.0±0.0). This was also consistent with our observations. Participants showed interest and curiosity through the questions they asked (reported above). When asked how much they liked the 3D tangible letters, results showed that most participants really liked them (mean=3.8±0.5). We also observed that most children held, played with, and manipulated the 3D tangible letters for most of the session time. P1 even said, "I got more babies today!" when new letters were added.

How Individual Characteristics Affect Learning Gains

Attentional Challenges

The teachers reported that P1, P4, and P8 had attentional challenges during learning. Based on the teachers' feedback, we assigned 1 (Yes) and -1 (No) to represent whether a participant had attentional deficits. The results of a point-biserial correlation test showed a significant correlation at the level $p<0.05$ between the participants' attentional challenges and their learning gains ((post-test score – pre-test score)/(full score-pre-test score) [19]) on trained word reading (r_{pb} (6)=0.730, p=0.040), with the participants who had no attentional challenges achieving more learning gains on trained words reading (1.0±0.2 versus 0.9±0.3).

Of the children with attentional challenges, we found that P1's gains on reading and spelling were larger than those of P4 and P8. We suggest that this is because P1 was distracted by features of system related to the task at hand (the pictures) but the others were distracted by letters not in use for the task (not related to the task at hand). Based on our observations, P4 and P8 frequently played with the 3D tangible letters while the facilitator taught them the rules. This may have reduced the amount of attention they could devote to listening and learning. However, P1 was distracted in ways that were more related to the task and so it was easy to redirect him. For example, P1 often made associations based on the current word or picture. When he saw the picture for the word *bait*, he left the seat and pretended to swim like a fish. He also closed his eyes and tried to look for letters through feeling and touching. "Where is the letter *i*?" Enacting scenarios including learned words may have been distracting or it seems possible that it may improve learning through association of multiple representations of words, which is in line with O-G practices.

Motivation

Based on the teachers' feedback and our observation, we assigned 1 (Yes) and -1 (No) to represent whether a participant had great motivation in learning or exploring new things. The results of a point-biserial correlation test showed that there was a significant correlation at the level $p<0.01$ between the motivation and the learning gains on trained word spelling (r_{pb} (6) =0.887, p=0.003), with the participants who had greater motivation achieving more personal learning gains on trained words spelling (0.8±0.1 versus 0.4±0.1).

The teachers reported that P2 and P8 had little motivation for exploring new things in general. This was consistent with the results from the questionnaire that showed P2 and P8 had less motivation compared to others (e.g. P2 chose "some" and P8 chose "not at all" when asked if they would like to continue using the system). We also noticed that P5 was interested at the beginning of a session but he lost his motivation during the middle stage when he knew that he had to receive a reading test and he could not play with the system as he wanted (e.g. building the words he liked). Lower motivation may be related to inattention and is related to lower learning gains. Our observations showed that unmotivated children had trouble maintaining focus for the duration of a session.

How Individual Characteristics Affect Preferences

Temperament

The results of a Spearman's ranking-order correlation test showed a strong correlation at the level $p<0.05$ between children's temperament (extrovert/mixed/introvert) and their preference on 3D tangible letters. The participants who were more extroverted liked 3D tangible letters more (r_s (6) =0.800, p=0.017). We also noticed that more extroverted children liked to ask questions related to the 3D tangible letters more. For example, P5: "Is there any lights inside the letters?" P6: "How does the letter connect to the computer?" The results of the questionnaire also showed that the children who were extroverted liked the 3D tangible letters more than the children who were introverted.

DISCUSSION

Our results suggest that scripted instruction with PhonoBlocks was effective in supporting the children at risk for dyslexia in learning to read and spell six common rules. Based on our findings we suggest four design recommendations for TUI systems designed to teach the alphabetic principle. We suggest that our recommendations will also benefit typical children because all children follow the same learning process, although dyslexic children have greater challenges hearing sounds and attending to how letter position changes sounds. Another group who may benefit are children who learn English as a second/foreign language (ESL/EFL) (e.g. Chinese) because they often have poor PA and limited knowledge of the alphabetic principle. [5,31].

1 Use dynamic colour cues embedded in tangible letters to draw attention to letter-sound correspondences

Using dynamic colour cues embedded in tangible letters, which flash to draw attention to the moment when letters' sounds change, appears more effective than using static letter colours, as seen in other reading acquisition systems (e.g. [4,14]). Our results showed that flashing a colour within a letter(s) helped children notice that something had happened. They either immediately understood the meaning, asked about it, or expressed understanding when it was explained. Some changes were easier to understand (e.g. adding *e* in magic-e rule) than others (blends). When expected colour changes did not happen, children used this information to correct their spelling errors during their practice sessions.

Many reading systems use different colours for each letter, or for vowels and consonants (e.g. Tiggly and Osmo). In our approach we use only a small number of colours to highlight parts of words (groups of letters), which helps draw attention to the letters that are important in each rule. Specifically, we use the colours to represent key elements of the rules and use white to represent the other parts of the word. We use flashing colours to highlight the moment of change. This design approach helps the children to focus on the part of the word relevant to the rules rather than on the whole word or on individual letters.

2 Create 3D tangible letters forms and workspace to enable epistemic actions, which simplify spelling and reading tasks

Epistemic actions are actions used to change external elements in the world in order to simplify a task [1]. Previous research has suggested that TUIs may encourage more epistemic actions compared to similar GUIs [1]. Our results showed that the 3D tangible letters enabled several types of epistemic actions. 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 an appropriate size and crafted with robust and safe (e.g. no wires) materials so that children can easily pick up or hold groups of them with their hands. The appropriate size here also means that there is enough space on the table to place all the letters with room to group and sort them; (2) letters should be able to stand up on their own so children can easily organize them in space; and (3) they should have both physical constraints (e.g. on the bottom) and visible marks (e.g. on top) that enable children to quickly recognize each letter and orient it correctly in space (e.g. *d*, *b*, *p*, *q*).

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

The stand-alone 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 tutor and child to handle them (e.g. place in slots) helps focus attention to the letters. This is consistent with the previous theories that showed the use of kinaesthetic/tactile modalities could improve learners' attention and memory [10,20]. If letters are light and robust, letters not in use can easily be moved away with an arm swipe. If letters are easy to handle, children can use single and two-handed interactions, which reflects their understanding of letter-sound structures and enables a facilitator to see learning happening in real time, and provide appropriate feedback.

4. Provide blend/decode function to enable children to learn how individual letters combine into blended sounds in words

The blend/decode function enabled children to construct whole words by hearing whole word sounds (swipe right) and then deconstructing words into individual letter colours and their sounds (swipe left). This function can help children practice their PA and decoding skills by seeing and hearing the changing letter colours and corresponding sounds.

LIMITATIONS

The main limitation of our study is the small sample size. Although we examined the participants' reading and spelling gains, due to the limited number of participants and the nature of a case study (without a control group), we cannot make a strong claim about the effectiveness of our system. However, our quantitative results are encouraging. In terms of design, our qualitative analysis of video and observational data enabled us to provide evidence for key design features that enabled behaviours we know contribute to, or are correlated with, learning. Based on our mixed-methods results we suggest generalizable guidance about specific design features which may be useful for others to explore and evaluate. In the future a more wide-scale controlled experiment would enable us to make stronger claims about the effectiveness of our entire system. In addition, a study that separates the effects of different elements of tangibility would contribute to design knowledge about why and how tangibility matters. Both are needed.

CONCLUSION

We present the design and evaluation of a tangible reading system for children at risk for dyslexia. Our system is the first to leverage tangible features of embedded dynamic colour cues in hands-on 3D tangible letters, alongside features shown to be important in other reading systems (e.g. linked representations, blend/decode function). Our system focuses on at-risk readers who are challenged to master PA and the alphabetic principle. The results of our case study showed that all eight children achieved significant gains in reading and spelling on trained and untrained words after instruction with our system and they maintained learning one month later. 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. In addition, we discovered that children's individual characteristics influenced their learning gain and preferences. Based on our results we proposed four recommendations.

Our work suggests that tangibility matters because reading is, in part, spatial. Letters can be represented as objects that have spatial-visual properties. Words are linear sequences of letters. The position of letters in the words dictates the sounds in the words. 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 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 makes 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, dyslexic, and ESL/EFL children.

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