From Tangible to Augmented: Designing a PhonoBlocks Reading System Using Everyday Technologies

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Abstract
This paper presents an augmented reality (AR) system that supports early reading and spelling acquisition of English for children. The design of the AR system was based on and extends our prior tangible reading system called PhonoBlocks. In this paper, we discuss why and how we extend the work from PhonoBlocks to an AR system design. The goal of our system is to teach children explicit letter-sound correspondences. Two key design features of our system, which are different from other systems, are the use of augmented dynamic colour cues and 3D physical lowercase letters that help to draw children's attention to how letters' positions in words change letter sounds. Unlike our previous system, our AR system uses off-the-shelf technology so it can be easily scaled and distributed. We discuss the advantages and opportunities for our AR solution, and outline our future plans for evaluating this system.

Author Keywords
Tangible user interfaces; augmented reality; children; early reading and spelling acquisition.

ACM Classification Keywords
H.5.2. Information interfaces and presentation: User Interfaces.K.3.1 [Computers and Education]: Computer Uses in *Education-Computer-assisted instruction*.

Figure 1: PhonoBlocks contains a touch based laptop, a customized platform and a set of tangible letters with LED lights (*up*). LED strips change colours to indicate letter sound change. In the Magic-e Rule, the colour *a* changes from yellow to red to indicate sound change from short to long (*middle and down*).

Introduction

Successful early literacy acquisition of alphabetic languages requires children to learn phonological awareness (PA), which is the ability to manipulate sounds in oral languages, and the alphabetic principle (AP), which is the rules of how letters represent sounds (letter-sound correspondences) [3]. Yet this is a challenging task for children to master, especially in languages that do not have consistent letter-sound correspondences such as English. Approximately 10% of children in English-speaking countries have difficulties in learning to read and spell (also referred to as "dyslexia") [3]. A larger number of children who learn English as a foreign language (EFL) face similar challenges [4]. Both groups of children may have poor PA and limited understanding of AP [3,4]. Traditional phonics-based instruction that uses an explicit, intense, and multisensory approach to stress the acquisition of AP, has been effective, particularly for at-risk and EFL children [3]. However, these instructions do not involve computational materials and rely on highly trained tutors, which are not available to many children.

Recently researchers have suggested the potential of tangible user interfaces (TUIs) in supporting learning to read for children [5,6]. In our prior research we designed and evaluated a tangible system called PhonoBlocks that uses embedded dynamic colour cues within 3D lowercase tangible letters to help children at-risk for dyslexia and EFL children (ages 7-9) learn to read and spell six alphabetic rules of English [6]. Despite the positive evaluation results, our PhonoBlocks solution is limited because it is comprised of custom hardware, including an electronic letter-making platform and 3D plastic tangible letters. The reliance on custom hardware makes it difficult to scale and distribute for use in schools. What is needed is a new system that utilizes widely available technology that can provide the same functionality as PhonoBlocks.

Smartphones and tablets (e.g. iPads) are becoming ubiquitous. Many schools use them in classroom instruction for children. Apps for these devices can be designed to support augmented reality (AR) using the camera feature. AR can be used to present a visual overlay on top of physical objects. We may be able to use AR to present a visual overlay version of our dynamic letter colour cues and 3D animations that is displayed on top of physical (rather than tangible) letter tiles. We can also use the device's speaker to play associated letter sounds. Our goal is to design and build an AR version of PhonoBlocks that uses readily available technology and rather than custom hardware. If we can create the same functionality, an AR version, if effective, would be scalable, easier to distribute and remain a cost-effective solution compared to resource-intensive reading programs.

AR Reading Systems

There are several AR reading systems, but most focus on teaching children storytelling [2,7,8,11] or whole word spelling [1,10]. Billinghurst et al. first proposed the concept of the MagicBook, a mixed reality interface that uses a real book to seamlessly transport users between AR and virtual reality [2]. Although this system was not specifically designed for children, it first demonstrated a proof-of-concept design of AR book. Mahadzir et al. [8] and Vate-U-Lan [11] took this concept and developed their AR pop-up books to teach English storytelling to children in Malaysia and Thailand. Observational and interview results in [8] showed that the AR technology increased children's

Figure 2: The AR PhonoBlocks system: a tablet running an AR app and a set of magnetic physical letters with black markers.

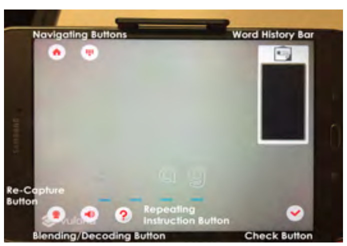

Figure 3: The interface of the Practice Mode: the system plays the audio instruction "Make the word *flag*" and the child needs to build the word using physical letters and scan them under the tablet camera.

attention and interest. Observational results in [11] revealed that all children showed initial interest in the lesson and interest was retained during the lesson. Hornecker and Dünser focused on the use of an AR storytelling book with typical and at-risk children (ages 6-7) [9]. However, the results showed both groups had interactional issues with the AR books, and the AR-books seemed not to increase children's general interest in books.

Barreira presented a AR system that used a computer, a webcam, and a set of squared paper-based picture markers to teach children word reading and spelling [1]. However, the system focuses on whole word spelling rather than alphabetic rules. Silva et al. presented ARBlocks, a projective AR block system that aimed to help children improve their reading skills [10]. In ARBlocks, a webcam detects the makers on blocks and a projector projects the augmented information such as pictures onto the blocks. However, all their learning activities are on-set and rime rather than letter-sound correspondences. To sum up, few studies have focused on designing AR systems that teaches children the alphabetic rules of English. This is what we target.

Prior Work on PhonoBlocks

PhonoBlocks was designed based on theories of dyslexia and EFL, best practices of multisensory instruction, and research on the specific advantages afforded by TUIs for hands-on learning [5].PhonoBlocks has two key design features that make it unique and effective: embedded dynamic colour cues and 3D tangible letters. Children learn different rules in the AP by placing one or more 3D tangible letters into slots on a word-making platform. Visual feedback is embedded in the 3D letters using LED strips that change colours to indicate sound changes. Visual and audio feedback are also provided on the digital display using coloured 2D letters and playing associated letter sounds (Figure 1). We conducted two case studies to evaluate the viability of PhonoBlocks with eight monolingual English-speaking children who are at-risk for dyslexia and 10 Mandarin-speaking EFL children [4,6]. The results showed the children in both studies achieved significant gains in reading and spelling trained and untrained words after PhonoBlocks instruction compared to their baseline performance, and the at-risk children also maintained their gains one month later. The results also suggested that dynamic colour cues with colour flashing attracted children's attention to the moment that letters change sounds while 3D tangible letters enabled epistemic strategies, such as ordering, to make the spelling tasks easier than if they were printing on paper.

AR PhonoBlocks Design and Implementation

Learning goal

The learning goal was to help children aged 7-9 years old learn to read and spell a set of words based on six rules of the AP. We used the same lessons developed in PhonoBlocks, which have been validated by teachers at the schools and an educational expert [6] (Table 1).

Design goal and requirements

Our design goal was to create an AR version of the reading system that has similar functionality to PhonoBlocks but uses readily available technology. Based on previous requirements, outlined in [5,6,9], our new system must include: **dynamic colour cues**: colour-code letters by the sound they make in any context for both single and multiple letter groups; display dynamic colours overlay on top of physical

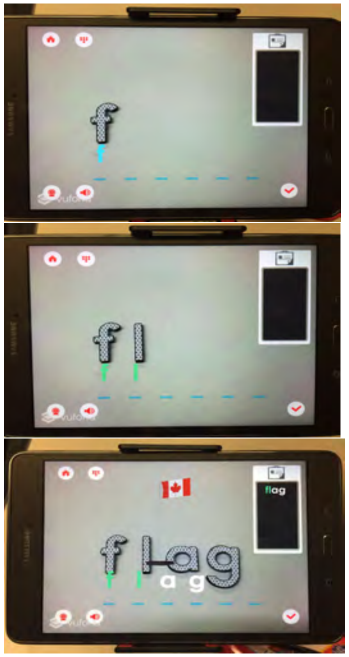

Figure 4: In the Learning Mode, the child learns the *fl* consonant blends through the word *flag*. The letters change colours to indicate the sound change during the word-making process. The child then clicks the Check Button, and the system plays the 3D augmented flag animation the sound, and generates the *flag* word in the history bar.

letters on the screen [6]; **3D lowercase letters**: that allow children to trace mirrored letterforms [5] and enable epistemic actions [6]; **multimedia feedback**: coloured letters, letter sounds, and animation are provided to create a multisensory learning environment [6,9];**hands-on interaction**: additional tools enable children to use two hands to manipulate physical letters and easily line them up to make words [6,9]; and **two modes**: the child can use the system with a teacher or alone [5].

AR PhonoBlocks system

AR PhonoBlocks is an AR system that supports the learning and practice of English AP for children. The system consists of a tablet running an AR app and a set of black magnetic physical letters (Figure 2). The tablet can be placed on a tablet stand so that the child can use two hands to interact with the physical letters. In the Learning Mode, the child can use the physical letters to make a word and see the augmented overlay of colour-coding letters shown on the screen during the word-making process. The child can also check the word meaning and sound (Figure 2,4). In the Practice Mode, the child can practice the learnt rules through word-building games (Figure 3).

Augmented dynamic colour cues

Based on the previous studies of PhonoBlocks [4,6], we slightly revised the dynamic colour cues and applied them to this AR system. We used blue for single consonant letter and green for consonant pairs; red for long vowel and yellow for short vowel; orange for vowel pairs; purple for r-controlled vowel pairs; pink for blended letter sounds (words); grey for a single letter in the pair; white for letters that are not related to the rules (Table 1, Figure 4). We also used colour flashing to indicate the letter sound change. For example, in the magic-e rule, the letter *a* in the word *game* will flash to indicate its sound changing from short to long when an *e* is added.

Magnetic lowercase letters

We used magnetic black lowercase letter tiles that can be easily purchased online (Dowling Black Lowercase Magnet Letters). We used the pure black letters because we do not want colours on the physical letters to distract children. Unlike most AR apps that use AR picture cards or blocks with 2D uppercase letters, we used 3D lowercase letters because lowercase letters constitute the majority of printed text, and 3D letters with hard edges enable children to easily touch or trace letters, an action of which seems to be beneficial to learning [3,5]. We also chose magnetic letters because they are commonly used in schools, and can be used alone or with whiteboards for an easy line-up.

Freezing and unfreezing augmented overlay

We provided multimedia feedback associated with the physical letters. Here we added a function that enables the users to freeze or unfreeze the augmented overlay. That is, when a teacher or child clicks the Check Button to submit the answer, the 3D coloured letters and animation will stay on the screen until the user clicks the Re-Capture Button (Figure 3). We added this feature only in the AR version because this function allows the teacher or child to carry the tablet in their hands to view the augmented 3D animation from various angles once they have competed the word. We did not have this function in the Tangible PhonoBlocks because there is little chance for them to carry the heavy laptop during use.

Learning Activities	Examples
Consonant Vowel Consonant (CVC): CVC patterns	*bet, pet,*
Consonant Blends: two consonants make a blended sound	*f→fl→ flag*
Consonant Digraph: two consonants make one sound together	*t* (*t* flashes green and turns grey) →*th*→ *thin*
Magic-e Rule: vowel sound changes from short to long when an *e* is added at the end of word	*gam* (*a* flashes yellow) → *game* (*a* & *e* flash red and *e* turns grey)
Vowel Team: two vowels make one sound together	*e* (*e* flashes orange and turns grey) →*ea* → *eat*
R-Controlled Vowels: r-controlled vowel pairs	*a* (*a* flashes purple and turns grey) →*ar*→ *art*

Table 1: Six rule-based activities and colour-coding schemas (black text = white colour).

Tablet stand, whiteboard, magnetic ruler & projector
Many everyday tools can be used to better support the learning experience. For example, the tablet can be placed on an adjustable tablet stand so that the child can have two-hand interaction with the letters and immediately view the augmented colour changes. Moreover, the whiteboard and magnetic ruler can be used to help the child to easily line up the letters. The teacher can draw lines on the whiteboard or use magnetic rulers to create physical constraints. These tools can be easily removed once the child gets better. The tablet can also be connected to a projector so the whole classroom can see the contents.

Learning Mode and Practice Mode
In the Learning Mode, the child learns with the system under the instruction of a teacher. The child/teacher can use the 3D letters to make graphemes, syllables, or words, scan these letters under a tablet camera, and then confirm, and the augmented content will be shown on the screen, including the dynamic coloured 3D letters, letter sound, and animation of the word. The teacher can build any words, even the pseudo-words as long as they follow the rules (e.g. *sab* in CVC). The Practice Mode allows the child to practice the learnt rules on their own. The system plays the word sound and the child spells the word using the letter set. If the answer is correct, the child will get rewards, otherwise they will get three levels of hints.

Technical solution
We used Unity and the Vuforia plugin to develop the software. The Vuforia was used to detect and track the marker on the lowercase letters and passes its identity to Unity which will run our customized app modified from PhonoBlocks. Here we provided various marker design files for letters that can commonly found at schools. Learners can download the online file and make their own letter sets easily

Discussion and Future Work
We have elaborated why and how we designed and implemented the AR system for supporting children's learning of the AP, building upon our prior 5-year research work. The AR version may have three advantages compared to our prior tangible version. First, we reduced the customized hardware but instead used everyday learning tools that most schools already have. In this way, we reduced costs and made the system more feasible for use in school contexts. Second, the augmented coloured letters and animation may better draw children's attention and elaborate word meaning compared to 2D pictures [4]. This may be more beneficial for EFL children who have little vocabulary knowledge. Third, the children can see the augmented feedback and their actions on the letters together through the tablet screen (co-located). They do not need to switch their attention between screen and letters (distal) [5]. Third, the use of white boards opens new opportunities for creative uses of the system, and also for future design of the system. For example, by using AI technology, the system may be able to recognize teachers' handwriting and drawings.

Another contribution is the technical challenge we identified for lowercase letter detection. We originally attempted to use the marker-less approach along with the Machine Learning technique to detect various lowercase letter fonts. However, it is extremely difficult in AR scenarios. Although most tools enable text detection (i.e. OpenCV, Vuforia, ARTookit), they only allow for whole word detection but not single letter detection. When using Machine Learning, we can detect single letter but the lagging time is extremely long in real-time video AR scenarios. In addition, several lowercase letters are very similar and are more likely to be mis-detected. Therefore, we switched to the marker-based solution. However, we would like to advocate other researchers to continue exploring potential solutions for lowercase letter detection in AR designs.

Our future work includes conducting usability testing with children to refine the design and then administering user studies to validate its use with at-risk and EFL children at public elementary schools. Specifically, we will conduct case studies to explore whether the AR PhonoBlocks can improve children's reading and spelling outcomes, and what features may or may not benefit their learning. We will also compare the results with our previous Tangible PhonoBlocks. We will also give multiple systems to teachers to explore how they will use them in various instruction contexts.

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