PhonoBlocks: A Tangible System for Supporting Dyslexic Children Learning to Read

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Abstract
Dyslexia is defined as severe difficulty learning to read. It affects about 10% of the population in English speaking countries. Severe difficulty learning to read is correlated with tremendous emotional, social and economic costs. In this paper, we describe PhonoBlocks, a tangible user interface to a reading system that uses dynamic colour cues embedded in 3D tangible letters to provide additional decoding information and modalities. PhonoBlocks was developed to support children, aged 5-8 years old, who are having difficulty learning to decode English letter-sound pairs. We present the theoretical foundations as rationale for our core design strategies and decisions. We discuss the assumptions in our design rationale and describe how we will validate our system working with a school for dyslexic children.

Keywords
Tangible user interfaces; dyslexia; children; reading; colour cues; tangible computing; Orton-Gillingham.

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. As a child makes the word “FADE” the colours of the vowel “a” change based on the sound it makes. The short “a” in “fad” is yellow; the long “a” in “fade” is red.

Introduction

Dyslexia is a specific learning difficulty that affects individuals’ language-acquisition skills, such as learning to read and write [3]. Each language has a unique *alphabetic principle*, the rules that relate single and multiple letter symbols with speech sounds. Children with dyslexia have difficulty learning and automating the alphabetic principle, and therefore have difficulty in word decoding and reading [6]. Recent research suggests that tangible user interfaces (TUIs) may have benefits for children’s learning, particularly in domains that involve space or physical properties [1, 8]. Letters are spatial representations. There is little research that has explored how TUIs might be designed to support children with learning disabilities to learn to read (for exceptions, see [4,10]). There are no studies that specifically investigate if using dynamic colour cues or tactile qualities of tangible letters improves reading outcomes for dyslexic children.

Theoretical and empirical research about dyslexia has highlighted the important roles of colour and tactile modalities in several perceptual and cognitive processes that may be related to reading. We applied knowledge from these theories to design a tangible reading system called PhonoBlocks. PhonoBlocks uses 3D tangible letters as both input and part of the output of a system designed to help dyslexic children learn the alphabetic principle for English. Specifically the system changes the colour of 3D tangible letters based on the sounds they make in a word, enables children to use letter shape cues by using traceable (with a finger) 3D letters as input and uses physical constraints of the 3D letters’ base to support correct orientation of the letters (e.g. p vs. q, b vs. d).

Theory

Colour Cues

The core challenge children with dyslexia have is learning the relationships between letters and sounds [13]. In the English language alphabetic principle letters and sounds are inconsistently matched. A single letter can have more than one sound. Multi-letter units, such as blends (“nk” as in sink), and stable syllables (“tion” as in motion) have consistent sounds but these sounds cannot be determined from the sounds of the individual letters. Learning to read involves learning rules that relate a letter's sound to its context (i.e., its position with respect to other letters within a word). For example, one rule is that a “'c” sounds like “k” before “a” and “o” but a “c” sounds like “s” sound before “e” and “i”. Another rule is that the stable syllable “tion” sounds like “shun”. English is particularly complex, and dyslexic children have difficulty learning these rules [7]. Explicating these rules improves reading and is a goal of many interventions [6].

We propose that colouring letters by the sound they make in a particular context, such that a letter's colour changes when the context changes its sound, may help dyslexic children more easily learn these rules. As a child changes the context, say by adding a trailing “e” to make “fad” into “fade”, colour of the letter “a” could change to reflect the change from a short “a” sound to a long “a” sound (Figure 1). An interactive system enables us to change a letter’s colour to reflect the sound it makes in particular context, which may draw attention to the rule. Similarly, letters placed in stable syllables (e.g. “tion”) could each adopt the same colour, which could help children group and remember these units. Based on this theory, our first design requirement was that that colour should be used to

Figure 2. Twenty-seven opaque traceable tangible letters.

Figure 3. The magnetic notch on each letter and openings in each slot utilizes physical constraints to enforce correct orientation of each letter in its slot.

highlight letter-sound rules for single letters and multi-letter units.

Other challenges dyslexic children have are identifying and discriminating adjacent letters, shifting attention between letters and maintaining previously viewed letters in working memory [6]. Colour cues may also help dyslexic children address these challenges. The atypical letter recognition of dyslexic children seems to be attributed to difficulties they have resolving some letters' differentiating features, such as high-acuity details (r versus i) or reflections (p vs q; b vs d)[6]. By comparison, colours are much easier to discriminate [14], and the colour perception of children with dyslexia is typical or superior [2]. When letters are coloured uniquely, they may be easier to recognize. Compared to 2D letter shape, colours are more memorable, less susceptible to crowding, and make better targets for visual attention [14].

Our secondary design requirement was to use visually distinguishable colours to help children differentiate and remember adjacent and confusable letters.

Tactile Cues
One emerging theory argues that the difficulty that dyslexic children have in identifying similar letters may due to the *mirror generalization* that human brains have evolved over millions of years of evolution to recognize 3D objects [11]. Mirror generalization may help people easily recognize 3D objects in the real life, but it is detrimental for identifying 2D letters, particularly those mirrored ones such as p and q or b and d.

Research in support of Orton-Gillingham (O-G) reading programs has found that teaching children to use their fingers to trace letters may improve reading outcomes by helping them associate letter shapes with distinct motor gestures [3]. Based on this theory we propose that using tactile cues inherent in traceable 3D tangible letters may further improve reading outcomes. 3D letters also enable us to use properties such as texture, colour, and location to convey information that may improve learning the rules for decoding the alphabetic principle.

System Design and Implementation

Learning Goal
The main learning goal was to help dyslexic children, aged 5-8 years old, to improve their understanding of the rules that are part of the alphabetic principle for English, including learning both single and multiple inconsistent letter-sound correspondences.

Design Goals: Colour and Tactile Cues
Our main objective was to create a system that we could use as a research instrument to explore the benefits of adding colour cues and using 3D shaped tangible letters as an interface to a reading system that supports dyslexic children to learn letter-sound correspondences. Based on our requirements, we proposed two groups of design goals: (1) *Colour cues*: colour-code letters by the sound they make in any context for both single and multiple letter groups; display dynamic colours inside 3D letters as well on as display screen (2) *Tactile cues*: design 3D tangible letters so that their size, texture, and shape are easily traceable; design letters so that child can physically (using tactile cues) distinguish the orientation of mirrored or flipped letters.

The PhonoBlocks System
PhonoBlocks is comprised of a touch-screen laptop, an input platform with seven slots, and twenty-seven

tangible Latin (English) letters in upper case (Figure 2). We provide an extra "e" to allow more combinations of vowels. The twenty-seven tangible letters were made with semi-transparent acrylic, with a height of 3 inches, a width of 2.5 inches and a depth of 1.5 inches (as shown in Figure 1). Each letter is fixed on a small acrylic base that enables them to stand and fit into the platform slots. Audio-visual feedback is provided on the digital display including the 2D letter(s) and letter sound(s). At the same time, visual colour feedback appears inside the opaque 3D tangible letter(s) once placed in the input platform's slots.

We are co-designing learning activities with teachers at a school for children with dyslexia, and the actual software associated with learning and practicing the alphabetic principle is completely flexible. Many different activities can be programmed around the core functionality of using the tangible letters. A typical activity might be one in which the system displays a coloured letter-sound pair (e.g. green EA) on the screen. The child is asked to make a word with that combination using the tangible letters (correct answers: EAT, MEAT) and the system provides feedback. Our intention is that children would use PhonoBlocks as an interface to reading software (ours or others') which is related to their curriculum's phonics activities.

Implementation of Colour Cues

Colours were mapped to letters according to their sounds. Consequently, letters adopt different colours according to the context, and different letters adopt similar colours when they sound similar, such as unvoiced 's' (as in sip) and soft 'c' (as in circle). Likewise, when multiple letters create a stable sound unit, such as a digraph ("AE"), blend ("SN") or syllable ("TION"), they adopt the same colour. Otherwise, adjacent letters have different colours. Visually confusable letters are almost never coloured the same.

In order to support colour cues, each letter contains a programmable LED strip. Each letter has a unique arrangement of electronic pogo pins under the bottom of the base which serves as its ID (Figure 3). The input platform contains an Arduino microprocessor that can identify each letter and pass the letter identity and location (slot number) to a custom application running on the laptop written in Processing. When a letter is inserted into a slot, information about the letters' context (e.g. slot number, and which letters are in other slots) is sent to the Processing application. The Processing application then triggers the correct letter sound and sends the correct colour information to the Arduino which then causes that colour to be displayed inside the opaque letter (Figure 1).

Because this is a work in progress, we have not finalized our mappings of colour to sound. Research in cross-modal perception suggests a few promising colour mapping schemas. Wrembel [16] documented *innate* associations between colours and vowels. Watson et al [15] uncovered some evidence that letter shape and frequency affect *synaesthetic* colour-letter associations. Simner et al. suggest that *semantics* may influence colour-sound associations and suggest the use of metaphoric mappings [1, 12]. Our schema may combine elements of innate, synaesthetic and metaphoric approaches, and will be validated by teachers and through a series of small experiments that are part of our ongoing design process.

Implementation of Tactile Cues

The letter size and material was chosen to allow a child to easily grasp, hold, or play with a letter with their hands. The hard edges support tracing. When a child's finger goes over the edge they can immediately feel that their finger has gone over the edge. The features of letter shapes are more salient when children trace 3D letters compared to sandpapers. Children can "feel" the differences between letters by simply grasping them.

We used a physical constraint on manipulation (as described in [9]) to help dyslexic children determine the correct orientation of letters. Each letter has a magnetic, notch on its base (Figure 3, red circle). Each slot has a matching magnetic hole. If the orientation of the letter is correct, the letters' notch fits into the hole and, as additional tactile feedback, the magnets provide a satisfying "click", much like how it feels to close a MacBook. If the letter is not oriented correctly, it does not fit into the slot. The use of this simple physical constraint creates tactile feedback so that a child can easily recognize the correct orientation of each letter without having to visually attend to them.

Discussion

We have outlined our rationale for colour-coding and using tactile cues with tangible letters. In many O-G programs, children often trace coloured letters on sandpaper or posters. Our tangible letters may have three main advantages compared to the traditional O-G approach. First, tangible letters provide an opportunity to leverage the use of physical characteristics of objects (e.g. textures) in learning activities. The multiple cues simultaneously embedded within the object may help children to memorize and understand letter-sound correspondences. In PhonoBlocks, we used the LED strips to create dynamic colours of a letter based on its letter sounds. Although we have not implemented the texture cues, there is a research opportunity to explore the possibilities of other learning materials in future iterations [5]. Second, tangible letters not only enable children to trace letters, but also allow them to physically manipulate letters in the space. The child can group a set of letters together to make up of a letter combination, or practice how to decode a word into a set of subunits. The physical manipulation of concrete letter objects may offload children's cognition or improve their understandings of abstract decoding concepts [1]. Lastly, the tangible letters with physical constraints may enable children to correctly use canonical orientation for letters, particularly for mirrored ones (p,q,d,b). Although we have focused on pronunciation rules and discriminating letters, older children may benefit from a coding scheme that highlighted grammatical or morphological rules; for example, picking out syllables, morphemes, or syntactical structures.

Future Work

Our next steps include user studies to validate the colour mappings and to refine the learning activities. As part of our co-design process, we are currently conducting focus groups with teachers in a school that specializes in working with children with dyslexia. Once complete, we will use PhonoBlocks as a research instrument in a pre-post controlled experiment in the school to investigate if systematic, long term use of our system with the school's learning activities improves reading outcomes for dyslexic children.

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