# The Code of Many Colours: Evaluating the Effects of a Dynamic Colour-Coding Scheme on Children's Spelling in a Tangible Software System

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**ABSTRACT**
Dyslexia is a severe impairment in reading and spelling that affects 10% of children in English-speaking countries. One area of difficulty is learning spelling rules that require attention to other letters within a word (i.e., context): for example, why *grapple* requires two *p*s while *staple* requires one. Poor visual attention contributes to children's difficulties. Computer-based programs that use multisensory cues have helped children learn simple letter-sound relations, but not contextual spelling rules. In this paper we present three theoretically derived principles that can be used to design dynamic colour codes for a variety of contextual spelling rules in software systems. We discuss how we used our principles to design the colour scheme for a single contextual spelling rule in our tangible software system, called PhonoBlocks. We evaluate its effectiveness in a field study with nine dyslexic children. On the basis of our findings, we conclude that our approach to using dynamic colour may help children with dyslexia to learn contextual spelling rules, but that individual factors impact the colours' effectiveness. We conclude by suggesting ways our dynamic colour-coding principles can be implemented in other systems taking into consideration individual factors that also impact their effectiveness.

**Author Keywords**
Tangibles; dyslexia; children; spelling; design; evaluation.

**ACM Classification Keywords**
H5.2. Information interfaces and presentation: User interfaces. K.3.m Computers and education: Computer-assisted instruction.

## INTRODUCTION

Dyslexia is a severe impairment in reading and spelling that affects 10% of children in English-speaking countries [42].


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Dyslexia has social and emotional costs. Children with dyslexia have typical intelligence and can excel in other fields (e.g., science or math), but the emphasis that school places on reading and spelling can discourage children from pursuing careers in these fields [13]. Reading and spelling difficulties result in negative childhood experiences, which can develop into low self-esteem and other emotional problems [24]. For these reasons it is important to develop interventions that help children with dyslexia become fluent in reading and spelling at an early age.

Dyslexia is multifaceted and has multiple sources (e.g., neurological, phonological or attentional disturbances). Although no one factor is responsible, interventions that focus on one factor can help [6,44]. *Poor visual attention* is a factor that has earned recent theoretical interest for its consistency in dyslexic samples, links to phonological and attentional causes and amenability to computerized intervention [7,9,10,21,28,38,55]. Visual attention is needed to discriminate fine-grained visual detail, such as what distinguishes *t* from *p* [55], and to process displays involving many fine-grained elements (e.g., decode or produce pages of text) [21]. Poor visual attention causes problems for English-speaking children. In English, letters can represent multiple sounds and sounds can be represented by multiple letters. Therefore, Anglophone children must learn rules that relate the spelling of sounds to *context*, the other letters in the word [13,19,52,60]. To learn these rules, children must remember previously observed cases of the rule and apply them to new cases [13,52]. Because the rules involve multiple letters, children must attend to and process multiple letters at a time [19,21,55]. Poor visual attention decreases the number of letters children can attend to, which may prevent them from remembering and applying previously seen cases of spelling rules [10,28,37,54].

To support Anglophone children with dyslexia in reading and spelling it is important to design interventions that compensate for their poor visual attention. One compensation is highlighting the relations between letters and sounds using visual or non-visual features that require less attention [4,5,12]. For example, to help children relate the letter *m* to the /m/ sound, tutors may show children an *m*-shaped *m*ountain (visual, but without details) [18], make the /m/ sound (auditory) and have them trace the *m* form (*physical*) [5,12,26]. The technique of presenting material using multiple sensory cues is called *Multisensory instruction.* It is a core component of mainstream interventions for dyslexia [1,5,12,26,45].

Computerized approaches can increase the effectiveness of multisensory instruction [6,39,43,44]. Relative to paper and pencil, computerized programs can more flexibly alter the sensory cues with which words appear [39,43]. Thus, computer programs can show children the effect of changing letter context on English letter-sounds. Using multi-touch or tangible technologies, software can couple digital and physical cues. Coupling children's actions on letters to multisensory cues about letters may help children to connect visual letter context to sounds and spelling rules [37, 48, 26, 34].

So far, computerized interventions that leverage multisensory cues have focused on more fundamental literacy skills [6], such as learning consistent letter-sound correspondences [4,17,35,39,43] or identifying letters [48] or sounds [16,36]. What is lacking is knowledge about how to extend multisensory techniques to design computer-based interventions for learning contextual spelling and reading rules of English.

Our research fills this gap. In another paper [22] we focus on the overall design rationale for our graphical-tangible software system, called PhonoBlocks. In this paper we describe how we derived three design principles for creating rule-specific dynamic letter colour schemes, and we present our first evaluation of PhonoBlocks for a single colour scheme and spelling rule.

## THEORETICAL BACKGROUND

Our proposal for using dynamic colours is based on: the attentional and mnemonic benefits of colour and the typical colour processing of children with dyslexia.

### The Benefits of Colour

Processing colour involves less attention than processing fine-grained visual details [49,55,58]. Visual tasks (e.g., *search*) that are difficult with fine-grained features (e.g, *orientation*) are easier with colour [30]. For example, searching for a *t* among *l*s takes longer than searching for a *red* among *blue* dots [58]. Observers associate colours with visual [31,38] and non-visual [47] information with which they are co-presented; colour can then 'cue' observers to remember the information [31,38,47]. Finally, colour can help observers identify abstract relations, such as *similarity*, *difference* or *correlation*. Observers group elements having the same colour and differentiate those with different colours [60]. In information visualization, colour-coding categorical variables enables visual analysts to rapidly identify statistical relations [11,40,56].

### Colour Processing in Dyslexia

Children with dyslexia have typical colour processing [15]. Like individuals without dyslexia, they rapidly focus on uniquely coloured items and ignore differently coloured items [32,55], even when the stimuli have difficult-to-discriminate shapes (e.g., find a green *t* amongst red *l*s). Accordingly, children with dyslexia might have an easier time identifying the patterns of letters, which underlie contextual rules, when the relevant letters are coloured (e.g., *ble* in *stable*). If the items have different colours, individuals with dyslexia can also process multi-item visual displays. For example, given two looks at a grid of differently coloured squares, individuals with dyslexia can detect whether a pair of colours swapped positions [38], though they cannot detect a similar difference in the identity of a letter between two looks at a word (e.g., *went* vs. *want*) [21,54]. Children with dyslexia may have an easier time processing contexts of letters, a type of multi-item display [7,9], if the letters are colour-coded. Finally, children with dyslexia can quickly retrieve information on the basis of colour but not upon contour cues [38]. For example, children with dyslexia perform poorly at switching between pressing a left or right key on the basis of an onscreen letter [21,50, 33]. But they switch swiftly and accurately on the basis of coloured shapes [55]. We suggest that colour cues may help children learn and retrieve spelling or reading rules.

## RELATED WORK

Several researchers have used colour to support children with dyslexia.

Hines' goal was helping children learn *rime-based decoding*. Rimes are the final vowel and consonants in words (e.g., *at* is the rime of *cat*). Because many words have the same rime (f*at*, s*at*), children can spell or read unfamiliar words by applying memorized rimes. This is *rime-based decoding*. Hines' scheme coloured rimes according to their vowel. For example, *et* in *pet* was green and *at* in *cat* was blue. Hines found that children who read words with these colours improved their accuracies for reading and spelling words that had the same rimes (e.g., *pat*), but not different rimes (e.g., *pot*). Hines concluded that her scheme helped children learn the rimes she taught, but not rime decoding in general.

Gattegno aimed to help children discover every contextual rule. Gattegno mapped different colours to each English speech-sound. Gattegno counted 100 unique sounds and used 100 colours. Gattegno exposed children to *word charts* in which letters were coloured according to their sound in the word. For example, *a* would be sea-green in *stable* but brown in *babble*. Gattegno believed that exposure to multiple examples would enable children to 'self-discover' the rules. Colouring the letters according to their sounds was supposed to highlight consistencies between particular words and sounds and support children in seeing them. For example, Gattegno expected children to learn the rule relating vowel sound to number of medial consonants by noticing: a) that the *a*s in *babble* and *snaggle* were brown but the *a*s in *stable* and *staple* were sea-green, and b) that the sea-green *a*s correlated one consonant while the brown *a*s correlated two. Gattegno did not explicitly evaluate his scheme.

Applying background theory in colour processing, we identify limitations of both approaches. Hines' scheme failed to highlight the distinction between vowel and consonant and thus failed to show children the general definition of rime. Lacking a sense of the general definition of rime, it would be difficult for children to appreciate that the strategies Hines taught them for the rimes *et* and *at* would also work for untaught rimes, and thus to generalize rime-based decoding to untaught rimes. Gattegno's scheme also failed to highlight similarities between multiple instances of the same rule. Instead, in colour-coding each individual sound, Gattegno's scheme may have encouraged children to attend to differences between words, not their similarities. For example, it would be difficult to perceive the words *title*, *maple* and *bugle* as a group (of single consonant-long vowel *consonant-le* words) if the words had few colours in common. Given that humans can remember around ten colour-value mappings [56], it is unlikely that children would be able to use Gattegno's 100 colour-sound mappings to notice correlated spellings and sounds. Neither approach addresses the difficulty that children have in noticing the *causal relations between* their spelling decisions and the sounds of other letters in the word [1,2,5,12]. Both approaches only showed children completed words in static colours, versus using colour to highlight the differences in the sounds of children's partial spellings, i.e., that when the child adds *e* to *stabl*, the sound (and colour) should change from short to long and (assuming Gattegno's colours) from brown to sea-green.

## DESIGN PRINCIPLES

In this section we present our three design principles that can be used to derive colour-coding schemes for any contextual spelling rule. We also review the benefits of a tangible reading system. We describe the coding scheme for the specific rule that we studied under *Methodology*.

### Three Design Principles for Dynamic Colour-Coding

Based on our literature review, we propose three design principles for choosing colour codes. **DP1**: colour codes should be specific to a particular reading or spelling rule. **DP2:** a colour code for a particular rule should only highlight information that is relevant for that particular rule. **DP3:** colours should dynamically change to draw children's attention to *moments of change* in spelling – times when a child makes a spelling decision by placing one or more letters.

Figure 1 (left) shows how we revised Hines' approach for the rime rule. The top row shows our revision. To draw attention to the rime, only rimes are coloured. To show the general definition of rime, vowels and consonants are differently coloured. To highlight the particular vowel sounds, which can be difficult for children to remember [2,22], each vowel has a unique colour. To maintain the consistency of the vowel group, the colours are from the same (warm) palette. Figure 1 (right) shows how we revised Gattegno's scheme. Gattengno did not colour-code for particular rules or use dynamic colour so our **DP1** and **DP3** do not apply. Instead he coded each letter one stable colour for all rules. We adapted his approach using **DP2**. For illustrative purposes, the top row shows the consonant-le rule with our scheme on the right and his on left. The bottom row shows changing vowels in simple words. We adapted his approach by only using colours to highlight letters that are relevant. The other letters are uncoloured. Restricting the colours to only relevant differences also limits the number of colours used.

Figure 2 shows how a software system could use dynamic colour. The system could change the colour of a letter (e.g. *u*) as a child spells another part of the word in order to re-focus their attention to the letter that changed (**DP3**) and help them appreciate the relation between the new sound and their spelling decision.


**Figure 1. Revisions of Hines (L) and Gattegno (R).**


**Figure 2: Software can change the colours.**

### Advantages of Tangibility

Our colour codes are a new way of representing spelling rules. Children also encounter rules in other forms: the sounds of the spoken words, uncoloured text or other spelling strategies (mnemonics, gestures). Our system supports children in connecting colour to these representations. One feature that helps children with dyslexia connect information across different modalities is *tangible interaction*: physically engaging with letters while experiencing other information about them [23,46]. Tangible interaction builds on Orton-Gillingham multisensory interventions, in which children handle or trace physical letters while hearing their sounds [26]. Recent experiments lend empirical support to the idea of using tangible interaction to help children with dyslexia connect letter forms to sounds [37] and to understand spelling rules [3].

## METHODOLOGY

### Research Instrument: PhonoBlocks

PhonoBlocks is an integrated graphical-tangible system that enables children to practice spelling by completing 'word-building' activities, which we adapted from paper and pencil activities [5,12]. We describe our design rationale in detail in [22]. Briefly we summarize our core design features below.

*Graphical Interface Features*
PhonoBlocks' graphical interface features are styled after features of multisensory interventions [5,12] (Figure 3). PhonoBlocks presents children with partially completed words. Words appear in the workspace. Completed words appear in the Word History. The colours of words in the history highlight similarities in relevant letters and support post-activity grouping of words that involve the same rule.


**Figure 3. The graphical interface.**

*Tangible Interface Features*
Children interact with PhonoBlocks through a tangible interface that consists of 46 clear plastic lowercase letters and a platform that has spaces for six letters (Figure 4). The platform represents the workspace. To add a letter to the onscreen workspace, children place the physical letter in the corresponding platform position. Each platform position and letter base is shaped so that letters do not fit into the slots unless children orient them correctly. The bases and platform positions are magnetized, so that when the child correctly orients and inserts the letter, the platform "pulls" towards and secures the letter base upon it. The satisfying "click" and feeling of solidity as the physical letter contacts the platform and the graphical letter appears onscreen supports children in learning the letter orientations and in connecting the graphical events to their spelling decisions.

**Figure 4. The integrated interface.**

*Dynamic Colours*
PhonoBlocks can support a variety of colour-coding schemes. Designers can specify a scheme for a spelling rule by mapping linguistic variables (e.g., letter location, identity, adjacency to other letters) to one of six colours. The LED technology determined the number of colours. PhonoBlocks detects many letter combinations, but here we focus on vowel sound category and vowel-consonant relationship relative to the consonant-le rule. As children spell the words, PhonoBlocks updates the colours of letters according to the active scheme and the letter context (**DP3)**. The colours apply to the tangible and onscreen letters. The simultaneous changes in colour of the onscreen and tangible letters were intended to capture attention and help children associate physical with digital letters.

*Implementation*
PhonoBlocks runs custom-written software that was implemented in the Unity game engine (v.5.1) and runs on a Sony Vaio laptop running Windows 8 with a touch interface. The letter platform houses an Arduino-mega microcontroller, which relays the identities of the letters in each platform position to the software and relays the new colour assignments to the platform positions. Each tangible letter houses an RGB LED strip. By changing the energies of the input at each of the RGB channels, the microcontroller causes the letters to glow in different colours. Each letter base has a unique configuration of magnetic pogo pins, which the microcontroller maps to the letter identities. The software renders the letters onscreen. Customized algorithms interpret linguistic variables as letter are placed, and according to the context (word and spelling rule) uses the active coding scheme to assign colours to letters.

**Study Design**
We designed a comparative study with nine children with dyslexia to explore two research questions:

**RQ1:** *Do our design principles result in a dynamic colour-coding scheme that enables children to effectively use colour to learn a contextual spelling rule?*

**RQ2:** *Are there consistent differences between children who are successful and unsuccessful in using the dynamic colour scheme to learn the spelling rule?*

We conducted our study at a school for children with dyslexia. Three tutors provided feedback on our study design and facilitated participant recruitment. The tutors had between 12 and 20 years' experience tutoring children with dyslexia using multisensory techniques.

*Contextual Spelling Rule: Doubling in Consonant-le*
For this study we focused on spelling because the tutors we worked with expressed that children struggled more with spelling than reading and computer interventions have been less successful in helping children with dyslexia learn to spell than to read [6]. We focused on a spelling rule that enabled us to address **RQ1**. As per **DP1**, we developed a colour-coding scheme for our rule. One rule identified by the tutors that students struggle with is spelling *consonant-le* words**.** Consonant-le words end in the stable syllable consisting of a consonant and the letters *le* (e.g., *stable* and *topple*). Spelling *consonant-le* words technically involves two separate rules: choosing the correct number of medial consonants on the basis of the vowel sound (sta*b*le not sta*bb*le), referred to as 'doubling**'**, and using the special *consonant-le* syllable (sta*ble* not sta*bul*). To double correctly, children must identify the relationship between

the vowel sound category (i.e., long or short vowel sound) and whether the following consonant should be doubled or not before adding the *le* ending. The identities of specific vowels and consonants do not matter. Based on our principle **DP1**, both parts of the *consonant-le* rule warranted dedicated colour schemes. We focus on the part of the rule that the tutors said their students struggled with – the doubling part – rather than adding the *le* ending.

### *Colour-coding Scheme: Vowel Long/Short Sound*

We applied our principles to design a colour-coding scheme, called V-DP (vowel colour based on design principles). V-DP colours vowels *red* when they are long and *yellow* when they are short (Figure 5, left), but does not colour-code vowel identity. We choose colours from the same end of the spectrum to show children that the two sounds were both vowels. We choose *warm* colours to match the intrinsic properties of vowel sounds, which are the 'high energy' (i.e., 'hot') nuclei of auditory words [22]. We choose *red* for *long* and *yellow* for *short* because *red* corresponds to *long* wavelengths and *yellow* corresponds to medium (i.e., shorter) wavelengths.

For a comparison we created a colour-coding scheme where each vowel had a specific colour: V-ID (vowel colour based on identity). Both schemes colour-highlighted the *consonant-le* syllable. Irrelevant letters are white. Our hypothesis is that children with the principle-based colour scheme (V-DP) that differentiates the *long* or *short* vowel sound category should use the vowel colours to learn the doubling rule but children with the scheme that differentiates specific vowel identity (V-ID) should not.


**Figure 5. V-DP (left) and V-ID (right) colour schemes.**

For the V-ID scheme we used five of our six colours to colour each vowel uniquely: *a* red, *i* yellow, *e* green, *o* blue and *u* cyan. We derived our mappings from cross-cultural biases that humans have to associate these colour palettes and vowels [57]. Because vowel identity is irrelevant to doubling, V-ID should not support children in learning the doubling rule. The V-ID group therefore served as a comparison by which to measure children's baseline behavior practicing spelling using PhonoBlocks. Although V-ID here served strictly as a comparison to V-DP, our principles predict that V-ID would support children in learning other rules involving specific vowel identity (i.e., spelling w*e*nt versus w*a*nt); the V-DP scheme should not. Future work will assess this complementary prediction.

In both schemes, letters that make up the *consonant-le* syllable are magenta (the remaining colour). Colouring the *consonant-le* syllable highlighted the difference between one- and two-consonant words, making the extra consonant easier to identify: one-consonant words feature a colour-magenta contrast whereas two-consonant words feature a white-magenta contrast.

### *Participants*

The tutors recruited ten children (five male, five female). We instructed tutors to choose children who struggled with the doubling rule. One child was colour-blind and his data were excluded. Children ranged in grades 3-7 but all performed below grade level at the doubling rule. Children provided verbal assent and their parents provided written consent. We randomly assigned participants to one of two groups, distinguished by the colour scheme they experienced: five experienced V-DP and four V-ID. Our low participant numbers do not enable us to make strong claims, but they do offer a coarse look at the how and whether children use the schemes and their effectiveness.

### *Procedure*

The study lasted four weeks. Three times a week, participants used PhonoBlocks to practice spelling two new *consonant-le* words. All children experienced the same words in the same order, selected from a list the tutors supplied. Each session lasted about 15 minutes. Each session followed an identical procedure. To ensure consistency between the sessions, the principal investigator facilitated the sessions. PhonoBlocks displayed a partially complete word and issued audio instructions to "make the word, *X*" (where *X* is the target word, e.g., *rubble*). The initial letters were the onset (e.g., *ru*, *ma*). Children only had to spell the *consonant-le* syllable and determine the number of consonants.

Apart from the dynamic colours, children received no feedback as they spelled the word. When children were satisfied they tapped the 'submit' icon to submit their word to PhonoBlocks (Figure 3, bottom right). If correct, PhonoBlocks showed the next word. Otherwise, PhonoBlocks produced an error sound. Children were given three chances to submit the correct word. After the third time, PhonoBlocks showed children the correct spelling and repeated the word, then showed the next word. Either way, completed words appeared in the Word History. After the child spelled both words the principal investigator used the Word History to review and explicitly map the rule to the colour codes. The script was adapted from how tutors explained the rules. The explanation was, "when we hear the [*consonant-le* syllable sound] we map it to the *consonant-le* syllable. If the vowel sounds short, the consonant must *bring its brother* so that the vowel is enclosed. Otherwise, the consonant leaves its brother at home. That way the vowel is open, and it sounds long." For children with the V-DP scheme, the principal investigator said "and when the vowel sounds short, it is yellow. If it sounds long, it is red". For children with the V-ID scheme, the principal investigator said "and each vowel is coloured and each colour is different." Either way, the principal investigator reinforced the vowel sounds by triggering PhonoBlocks to read the words aloud.

Children's tutors observed the sessions. During the first session, which served to show children how PhonoBlocks worked, the tutors modelled how to use PhonoBlocks as the principal investigator explained. Afterwards, the tutors did not intervene. The tutors' presence comforted the students and encouraged them to stay focused, and also better simulated the classroom contexts where PhonoBlocks is supposed to be used. The tutors' presence also enabled us to cross-check our observations of students' behaviour with theirs. Finally, the tutors provided a unique perspective on how the students' behaviour differed between using PhonoBlocks versus pre-existing mediums.

Before conducting the study, we confirmed that children understood the difference between short and long vowels and that children could perceive the colours. Children were asked to produce example long and short vowel sounds and to classify vowels in spoken words as long or short. Colour vision was assessed with an online version of the Ishihara test (http://colorvisiontesting.com/ishihara.htm).

### *Measures and Analysis*

**Quantitative:** Before and after the study, we measured children's accuracies for spelling 16 *consonant-le* words. Words were sampled from the same set as those used during the study. The pre-assessment provided a baseline for assessing the extent of children's improvement. To assess transfer these were subdivided into eight coloured and eight uncoloured words; on the post-assessment these were subdivided into four unfamiliar words and four from the pre-test. All tests were conducted using PhonoBlocks. PhonoBlocks recorded whether or not the child was correct. PhonoBlocks also recorded whether the child erred in doubling, adding the ending *consonant-le* syllable, or both.

The main dependent variable was the difference in children's pre- and post-assessment frequencies of doubling errors. Our purpose in collecting quantitative data was to acquire a sense of general trends and exceptional cases within our sample, to cross-check our qualitative impressions against objective assessments of children's performance, and to generate ideas for future iterations. Our sample size was too small and the children too variable to support inferential statistics; our claims are not inferential. Effect sizes capture the overall size and consistency of a trend within a group. Therefore, to convey a general impression of the trends within our sample we report effect sizes (using Pearson's correlation $r$). Following Cohen's convention, we consider .3 to .5 to be medium-size effects and .5-1 to be large effects. We expected children with the V-DP scheme to show large improvements in doubling but children with the V-ID scheme to show little improvement (**RQ1**). Children with dyslexia can yield highly variable behaviour, which overall effects can mask. To identify potentially relevant exceptions to overall trends, we supplemented our overall analysis with analyses of individual children (**RQ2**).

**Qualitative:** We collected several sources of qualitative data. The principal investigator observed and audio-recorded the sessions on her iPhone 4. The tutors observed the sessions. The principal investigator interviewed the tutors before and after the study. The interviews aimed to capture tutors' impressions of the system's feasibility and effectiveness, and to solicit ideas for future designs. The questions asked were: *1) Do you think the colour codes are effective? Why or why not? 2) Do you notice any differences in the students' behaviour when using PhonoBlocks than paper and pencil? If so, please describe. 3) Please describe any other observations.* The principal investigator also asked the children three questions that probed their understanding of the colour codes and spelling rule. The questions were a) what they thought the colours signified ("Do you remember what the colours mean?") b) [following the change to a colour] why the colour changed ("Can you explain why the *a* changed to red?" and c) [following a successful doubling] why it was necessary to double the consonant ("Why must we spell *rubble* with two *b*s? How come we can't spell it with one *b*?"). Responses were considered accurate if the student's explanation noted that (1) *consonant-le* is a separate syllable, which is divided away from the word's onset (2) the number of consonants determines whether the onset syllable is open or closed and this determines the sound of the vowel. The principal investigator transcribed the tutors' and students' interview responses on her laptop. Finally, tutors provided typed summaries about the students. The tutor-student confidentiality relationship permitted the tutors to divulge children's favoured school subjects and extracurricular activities and the tutors' general impressions of them.

Qualitative data were analyzed after the quantitative data, with an eye to addressing our research questions and to explaining the quantitative results. Applying background theory and our quantitative analysis, the principal investigator established four themes for categorizing the qualitative responses and refined them following an initial pass of the qualitative data. The themes are described in the results section.

## RESULTS

### Quantitative

At baseline, both groups doubled (median 50%) and correctly formed the *consonant-le* syllable (median 44%) around chance. At post-test, although both groups improved in syllable-formation, their doubling remained poor (~50%). Contrary to our expectations (**RQ1**), the children's colour scheme had little overall effect on their improvement ($r<.2$). Figure 6 summarizes these results. Next, we investigated whether these trends were consistent between new and unfamiliar and coloured and uncoloured words.

Although the V-ID group tended to double better with familiar than unfamiliar words ($r$=.6), all other effects were negligible (all $r$s<.1). Likewise, consistent with the absence of a strong between-group colour-scheme effect, neither group yielded strong effects of assessment word colour ($r$s<.3).

We identified two potential exceptions to the V-DP group's apparent inability to use the colors as supports. Two children (P2 and P5) who had the V-DP scheme improved in their consonant doubling. At post-test, P2 correctly doubled 7/8 coloured and uncoloured words, up by 5 and 6 words from pre-test. P5 doubled 8/8 words correctly, an improvement of 6 words from pre-test, but only for coloured words. His performance for uncoloured words was at chance (4/8).

**Qualitative**

In our qualitative analysis we aimed to understand whether and how the colours contributed to P2 and P5's improvement, and if so, how we could revise PhonoBlocks to help other children use dynamic colour to achieve gains like P2's and P5's. There were no obvious usability issues. Following the instructional session, all children were able to use PhonoBlocks to spell the words. Usability issues are therefore an unlikely explanation for the effects we observed. We organize the remainder of our analysis around four thematic categories: how children use colour, attentional focus, inferring associations between representations, and individual factors. Theme 1 addresses RQ1. Themes 2-4 address RQ2.

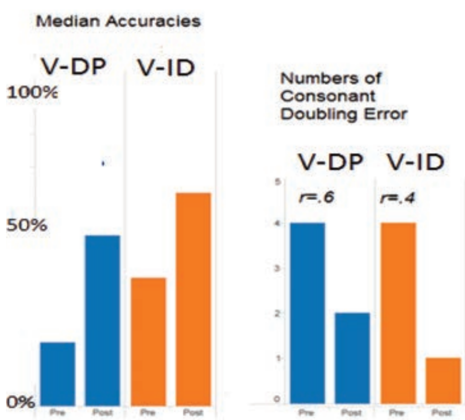


**Figure 6. Pre vs. Post Performance for the V-DP (blue) and V-ID (orange) group.**

**Theme 1. *How children use colour***: Four of the five children (P2, P5, P7, P9) who had the V-DP scheme appeared to attempt to use the colours to help them spell the words. The children's uses of colour can be explained by looking at differences in the accuracy of their associations between colour, vowel sound and spelling decision. No children with the V-ID scheme appeared to use the colours.

P7 and P9 learned and used the association between vowel sound (long vs. short) and colour to identify mispellings. In session six, P7 had to spell the word *title*. She initially produced the word *tittle*. PhonoBlocks detected the extra *t* and coloured *i* yellow. P7 responded: "We have to make it red". P7 removed the *l*, but appeared uncertain what do next. When asked why she wanted to "make the *i* red", P7 replied "because then it'd say *title*." Like P7, P9 appeared to understand the relation between vowel sound and colour, without understanding their relation to spelling. In session seven, P9 had to spell the word *ogle*. Like P7, her initial spelling (*oggle*) resulted in a yellow vowel. P9 responded, "It should be red". She replaced *gle* with a single *e* (forming *oge*). PhonoBlocks interpreted *oge* as a *consonant-e* syllable, in which the vowel is *long*, and coloured *o* red. P9 submitted *oge*, but never discovered the correct spelling. P9's behavior is noteworthy in that she appeared to retrieve an alternate but inapplicable way of spelling long vowels (i.e., P9 applied the *consonant-e* but not the doubling rule).

P2 and P5 also appeared to apply the colour-vowel association to identify misspellings. In contrast to P7 and P9, P2 and P5 also appeared to associate the colours or vowel sounds with the correct spelling. We observed this in sessions three (for P2) and four (for P5). Both children initially produced incorrect spellings (P2 spelled *wiggle* as *wigle*; P5 spelled *boggle* as *bogle*). Both children reacted to the colours by attempting to correct their misspellings; P2 and P5 used the right spelling. P2 inserted an extra *g* between *g* and *l*. When asked why he changed the word, P2 responded: "I remembered it was supposed to be yellow when it sounds short." P5 behaved similarly. When P5 finished his initial word, turning *bogl* to *bogle*, the *e* turned red. P5 reacted: "No, two *g*s". Like P2, he shifted the *g*, *l e* one space to the right, and inserted an extra *g* (producing *boggle*, with a yellow *o*). When asked why he changed the word, P5 responded "because it went red." Contrasting P7 and P9, P2 and P5 remembered the correct way to change the letters colours (and sounds).

From sessions one to five, P2 and P5's initial words erred strictly in the number of consonants. From sessions six to 12, both P2 and P5 produced the correct spelling *upon hearing the word* (P2: 100%. P5: 90%). This suggests that they associated the sounds of the words that PhonoBlocks read directly to the spellings, i.e., without needing to see the colours. On the other hand, the post-test with uncoloured words revealed that only P2 had this skill. P2 performed near-perfectly with coloured and uncoloured words. P5 performed perfectly with coloured words, but his performance with uncoloured words was at chance.

Consistent with his near-perfect post-test performance, P2 provided accurate answers to the interview questions. For example, explaining why *rubble* has two *b*s, P2 enclosed his hands over *ble* and said "because *this* is a syllable and" (he moved his hands to *rub*) "this is a syllable." When prompted to explain why the syllables mattered, he clarified that "it sounds short if it's closed". By contrast, P5's explanation of the two *b*s in *rubble* was "because the person made it that way."

We now compare P2, P5, P7 and P9 to the other children, and briefly summarize the other children's behavior. As with P2, P5, P7 and P9, children's initial spellings erred in the number of consonants. In contrast, these children did not use the colours to diagnose their misspellings. Instead, they relied on PhonoBlocks's error feedback, changing their misspellings (from one to two consonants or vice versa) after submitting them. Their explanations of the spellings and colour changes were suggestive of a preliminary but fragile understanding. They mentioned some of the concepts, mnemonics and gestures their tutors had taught them, but connected them in an incoherent way: "Because... we need to [*opens and closes hand*] make the word" (P4)/"Big brother... don't know" (P2).

**Theme 2. Attentional focus.** Poor attention is what impedes many children with dyslexia from effectively using computer-based interventions [1,6]. The tangibles attracted students' attention. Although students sometimes used them unproductively (e.g., to build towers), other uses might have helped the children consolidate material (e.g., tracing the tangible letter forms). Contrary to expectation, children tended to place their attention *either* on the tangibles or on the screen. Tutor 1 (T1) agreed. She imputed children's disregard of the colours to their disregard of the screen, on which the changes of colour were more salient. In addition, children seemed to show an effect of the narrowed attentional focus that is symptomatic of dyslexia. They focused strictly to the tangible letters they manipulated (e.g., the last *e* of *ble*), and did not notice changes to the colours of letters already on the platform (e.g., to the onset vowel). This suggests that the colour changes were insufficient to re-focus children's attention. Five children also appeared distracted by events external to the task and attempted to engage the principal investigator in irrelevant conversation (concerning: extracurricular activities, favorite movies, sports and weekend plans). P5 demonstrated the same lack of focus to the screen and non-productive engagement with the tangibles as the other children. P5 differed somewhat from the other children in that he also demonstrated curiosity about PhonoBlocks and progressed to using the tangibles in ways that matched their intended use. P5 is the only child who asked questions about how PhonoBlocks worked, including (at pre-test, before the colours were explained) why some letters were coloured. P5 is also the only child who spontaneously used the tangibles to spell other words. In session four, before PhonoBlocks indicated which word to spell, P5 used the tangibles to spell *dad*. P2's behavior differed from the other children's. P2 volunteered no information about himself and demonstrated no interest in the tangibles (or PhonoBlocks more generally) aside from being a means to finish the task. P2 finished quicker than the other children; it is possible that he was better able to focus on the task.

**Theme 3. Inferring associations between representations.** The colours were an alternate way of representing long and short sounds. To effectively use the colours, children had to understand that they represented the sounds of long and short vowels, i.e., that yellow represents the *ah* sound in *babble* and red the *ay* sound in *maple*. All tutors emphasized that their students had difficulty connecting alternate representations of concepts. T1 said, "If you use a different term, they don't know what you mean… and that's an awakener. We need to teach it to them in different ways." T1 attributed children's difficulty using the colours to their difficulty connecting the colours with other ways of understanding long and short vowels. Despite knowing that *red* and *yellow* meant *long* and *short* and that *ay* and *ah* were *long* and *short* sounds, children frequently submitted words in which the vowel colours implied the wrong sound. Such behavior is consistent with the idea that children have multiple ways of representing concepts but that children do not always connect them. Our participants could have associated the words *long* and *short* with long and short sounds, and the words *long* and *short* with red and yellow, without inferring an association between red and yellow and long and short sounds.

Inferring the association between red and yellow and long and short sounds would enable children to use the colours to diagnose errors, as did P2, P5, P7 and P9. To progress to using the colours to correct their errors (as did P2 and P5), children would need to further associate the colours with spelling decisions: placing either one or two consonants. This way, the colours could trigger their memory of the appropriate spelling decision. Children had several pre-existing mnemonics for recalling the spelling decision (the phrase, "big brother", a gesture, closed/open first for closed/open syllable, and an action, tapping each letter and sounding them out). All children showed explicit reliance on some of these cues (e.g., flexing their hands into the syllable gestures, muttering the mnemonics). The fact that children were unsuccessful at doubling the consonant suggests that these cues were ineffective. It is noteworthy that neither P2 nor P5 demonstrated reliance on these strategies after they demonstrated explicit use of the colours. Children who did not use the colours but relied on their pre-existing mnemonics did not appear to learn the connection between the colours and the number of interior consonants, despite the reflection period during which this connection was emphasized. The fact that P2 and P5 could double correctly (P5 in particular) only when the colours were present suggests that colours might be a more effective cue for some children than children's pre-existing mnemonics. P5's tutor expressed this sentiment. Observing P5's gains, she emphasized how the colors "lighting up for the short and long vowel" helped him to "get it", and thanked us for "teaching [her] student a difficult concept". The question is how to encourage more children to associate the colours to spelling decisions.

Finally, generalizing the association to uncoloured words would require children to infer a direct association between the vowel sound category (what children hear as PhonoBlocks reads the word) and spelling decisions, versus needing the colours as a memory aid. P2 is the only child in the V-DP group who appeared to spontaneously infer the connection between sounds and spellings, given the connection between sounds and colours. Other children may require more explicit support.

**Theme 4: Individual factors.** Factors unique to P2 and P5 may have encouraged them to attend to the colours or helped them to associate the colours with other information. Because we did not directly measure probable personality or cognitive factors, we can only infer them from children's favored academic and after-school activities. P2 and P5 had the same favorite subject, science, and after-school activity, building (i.e., with Legos, KNex). No other child favored these activities. Other children favored: art (7 children), PE (3 children) and tutoring (1). An interest in science might indicate greater-than-average curiosity and *attention* to detail. P2 differed from P5 in that he claimed to enjoy mathematics. An interest in mathematics could indicate greater-than-average ability to abstract patterns and to derive information from transitive associations [27], for example, if spelling decision associates colour and colour associates sound, then spelling decision associates sound.

## DISCUSSION

The case studies of P2, P5, P7 and P9 suggest that children can associate colour to vowel-sound category and subsequently use the association to diagnose misspellings. The case studies of P2 and P5 suggest that children can associate colours to the spelling and use the colours to retrieve them. Finally, P2's trajectory, from chance *consonant-le* spelling at pre-test to near perfect spelling at post-test, might suggest that children can use the associations between colour, vowel sound and spelling to derive a direct association between spelling and vowel sound, which enables them to spell words without needing the colours.

Several researchers have applied connectionist models of learning to explain how children develop literacy skills and the errors that children produce [3,4,19]. A connectionist model could also explain our results. In connectionist models, domains of knowledge are associative networks of interrelated concepts. Learning is the process of creating or adjusting associations between concepts [4]. Children err if they fail to associate concepts that should be related or associate concepts that should not [3,4,19]. Applying this model to our data, we might distinguish P7 and P9 from P5 and P2 and P2 from P5 in terms of the associations they formed. All children appeared to associate colour and vowel sound. Unlike P2 and P5, P7 and P9 seemed unable to further associate colour (or vowel sound) to spelling decision. P7 may have associated colour to an incorrect spelling (i.e., *consonant-e* syllable). Although P5 seemed to associate colour to vowel sound, and colour to spelling decision, he did not seem to infer a direct association between spelling decision and vowel sound. Therefore, without the colours he could not retrieve the correct spelling. P2 seemed to have the most accurate associative network, in that he recognized the direct connection between vowel sound and spelling decision. Other children could report that *red* meant *long* and *yellow* meant *short* vowel. They also understood which sounds corresponded to short and long vowels. But these children did not appear to infer the extra association between a letter's colour and how it would sound. As such, the colours did not cue them to their misspellings.

We identified poor attention and poor associative ability as two possible reasons why some children did not use the colours effectively. Poor attention has been implicated in dyslexic children's ineffective use of other multimedia programs [1,5]. Although we anticipated the threat of poor attention, there were two unanticipated consequences. First, that the colour changes were insufficient to overcome the poor attention; second, that the tangibles seemed to direct attention *away* from the colours, rather than helping children integrate the colours with their actions on the tangibles (i.e., their spelling decisions). These findings have implications for designers seeking to capitalize on the potentials of tangible ('learning by doing') and digital (multimedia delivery and structure) interfaces to implement learning activities. As the complexity of the learning content increases, so too does the amount of attention that each interface requires. Because tangible interfaces are inherently attention-grabbing [46], attention may be biased against the digital interface. Consequently, designers may need to provide children with cues that help them shift attention between the tangible and digital interfaces. In our case, given that it was easier to see the entire word on screen than in tangible form, it was important that children look at the screen after placing a letter that affected the word sound. Designing the tangibles to temporarily shut-off, or the screen to flash or emit a sound, are ways we and other designers could help children toggle attention between tangible and digital interfaces.

Poor associative ability has been implicated in math-challenged students' ability to use gesture-based supports for mathematical problems [27]. To our knowledge, ours is the first study to suggest that poor associative ability might also prevent dyslexic children from effectively using the multiple representations that multisensory approaches advocate. It is typically assumed that "more representations" are better [39]. Our results suggest a caveat: more representations are better only if children know how to connect them. When applied to teaching consistent letter-sound correspondences, the connection may be forged by simply presenting the multiple cues simultaneously. When applied to teaching contextual patterns involving dynamic properties, the connection may demand more of children's innate associative capacities.

Accordingly, P2, the only child who appeared to effectively associate the colours with long versus short vowel sounds (auditory) and spelling with one versus two consonants (kinesthetic), as well as to infer a direct link between sounds and spelling decisions, also expressed interest in a discipline (math) that demands considerable associative and inferential abilities. Our results suggest that designers interested in extending the principles of multisensory instruction to dynamic computer-based systems may need to provide children with cues about how to effectively integrate or connect representations. For example, we might use the reflection period with the Word History to explicitly show children the associative links between the colours and other representations of long and short vowel. Images of the closed and open fists could appear beneath the onset syllables and the pictures could be outlined in the corresponding colours, similarly to how colour has been applied to help older students integrate diagrams and text [47]. Likewise, we could have designed the relations between the colours, sounds and spelling decisions to better reflect their associative structure. Humans use temporality as a cue to causation. To prevent children from spelling the words through trial and error, we did not play the sounds of new words as children spelled them. Children only became aware of the sound after submitting the word, when PhonoBlocks read it. Because there was virtually no delay between the colour changes and children's spelling decisions, either of these could have appeared as the 'cause' of a sound change. P5's inability to spell with uncoloured letters might have attributed a belief that the *colours*, not the spellings, caused the sound changes. To better communicate the events' causal structure we could present the colours in a way that make them seem more like an effect, versus a cause. For example, we could impose a small delay between the spelling and colour changes, or we could make the colours offset after a short period. Either of these could serve to focus children's attention on the *spelling changes* as the primary cause, and reinforce the intended role of the colours as a transient attentional and memory cue.

Our study had several limitations. Our sample size was too small to support inferential statistics, so we cannot quantify the effectiveness of our colour-coding scheme. Second, we did not compare the gains of children using dynamic colour to those of children using PhonoBlocks without colours. The specific contribution of colour - as opposed to tangibility or overall novelty - is therefore unclear. Third, we only applied our principles to derive one coding scheme for one spelling rule. We need to derive other schemes for other rules and evaluate these before we can make any claims about our design principles. Finally, our interpretations of why P5 and P2 behaved differently from the other children are based on 'proxy' measures of the candidate causes, i.e., cognitive and personality factors, and are at this point speculative. Our observations form a basis for future research in which we will more rigorously measure these potential effects.

## CONCLUSION AND FUTURE DIRECTIONS

In this paper we outlined a strategy of using dynamic colour in an integrated tangible-digital multimedia interface to support children with dyslexia in learning English contextual spelling rules. We specified three principles for designing colour codes for software mediums: **DP1**. Colour codes should be tailored to specific reading or spelling rules. **DP2**. Colour should only differentiate information that is relevant to that rule. **DP3**. Colours should directly communicate how properties change according to context, i.e., colours should be dynamic. We instantiated our principles in a tangible research instrument, which we used in a mixed-methods study to gather preliminary observational data about how children might use dynamic colour and what stands in their way of using dynamic colour effectively. We uncovered evidence that children can use dynamic colour to self-diagnose misspellings. Children may subsequently use colour to retrieve strategies for correcting the misspelling. For some children, associating colour to sound and to spellings may be a stepping-stone to directly associating the spellings and sounds, and therefore of learning the rule. From our qualitative data we identified candidate factors affecting children's use of the colours and strategies by which designers could help children overcome them.

Our results contribute knowledge to the domain of developing multimedia computer-based supports for children with dyslexia. Our results may also generalize to integrated tangible and multimedia systems designed for other populations with attentive or associative challenges (such as ADHD) or for other domains involving abstract or contextual material, such as mathematics. Our next steps are using the data from this preliminary study to design a larger study in which we more rigorously measure children's attentiveness and associative abilities and see how they predict children's uses of colour. We will generalize our principles by assessing how well colour codes designed for other contextual rules (e.g., the V-ID scheme for vowel sounds), help children learn those rules. This will enable us to more rigourously evaluate our design principles. Finally, we will use our observations to iterate on the design of PhonoBlocks, and assess whether changing the interface by which we present the colour codes enables more children to use them in learning to spell or to read.

## SELECTION AND PARTICIPATION OF CHILDREN

Tutor consultants from the Kenneth Gordon Maplewood School for children with dyslexia recommended ten of their students for participation on the basis of their challenges in spelling. Students provided verbal assent and their parents provided written consent. All who consented participated.

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