Improving Hindi Decoding Skills via a Mobile Game

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Abstract

Previous research with alphasyllabaries has shown that children struggle with akshara that have two or more consonants, known as complex akshara. We developed a mobile game that teaches 4th grade children Hindi decoding skills, with an emphasis on complex akshara. All of the children were second language learners of Hindi. There were two versions of the game that varied in terms of stimuli spacing (massed and distributed). We found that the game improved participants' akshara recognition and their ability to read and spell words that contain complex akshara. There is also evidence of learning in the online data; participants were able to more quickly arrive at the correct answers as the game progressed. Both versions of the game yielded equivalent levels of improvement, but participants played the massed version faster. The spacing results are interpreted using the desirable difficulties framework. Overall, the results suggest that mobile technology can effectively improve akshara knowledge.

Keywords: Hindi, alphasyllabary, akshara, spacing, desirable difficulties, mobile technology, educational games, reading, spelling

Improving Hindi Decoding Skills via a Mobile Game

Hindi is a widely spoken Indian language; it is the official language in 13/29 states (e.g., Bihar, Uttar Pradesh, Madhya Pradesh) ("Languages in India," 2016) and thus most residents are native speakers of Hindi[1]. In states where Hindi is not the official state language (e.g., Maharashtra, Karnataka) many residents learn Hindi in school as a second language. Due to this system, Hindi is widely spoken with approximately 260 million native speakers and 120 million second language speakers as of 2016 (Lewis, Simons, & Fennig, 2016).

Hindi uses an alphasyllabic writing system, which is very different from the alphabetic and morphosyllabic writing systems commonly studied by today's research community. Due to its alphasyllabic writing system, Hindi poses some unique orthographic challenges to learners. Additionally, because of its fine phonological contrasts, Hindi poses some unique phonological challenges as well. Due to the large number of Hindi speakers, we need to identify effective methods for teaching Hindi. Furthermore, more research on alphasyllabic writing systems can shed light on the cognitive mechanisms underlying reading that are generalizable to all the world's languages.

Orthographic Challenges

In the alphasyllabic writing system used by Hindi, phonemes combine in a non-linear manner to form open syllabic graphs called *akshara*. Because there are more syllables than phonemes in language, alphasyllabic writing systems have very large graph sets (Nag, 2011). A large graph set also results in high graphic complexity (Chang, Plaut, & Perfetti, 2016).

There are three types of akshara based on number and composition of phonemes. *Simple* akshara either represent a vowel phoneme or a consonantal phoneme and an inherent schwa vowel (e.g., W /u/ or s; /sə/). *Consonant-vowel (CV)* akshara have consonant and vowel subcomponents (e.g., s;u /su/). *Complex akshara* contain two or more consonants and may also have a vowel subcomponent (e.g., st;u /s̪t̪u/) (see Table 1).

Even simple akshara can be relatively difficult to learn. There are many orthographically similar simple akshara that are easy to confuse (e.g., m; /m/ and B; /b^h/). The presence of many orthographically similar pairs can be challenging to novice learners (Gupta, 2008). CV akshara can be challenging because the vowel diacritics are arranged in a non-linear manner around the consonant.

[1] There are several dialects of Hindi (e.g., Haryanvi, Madhubani). In some Union Territories (e.g. the Andaman and Nicobar islands) Hindi is widely spoken and a link language but a second language for nearly everyone.

Complex akshara present an additional layer of difficulty. First, the rules for concatenating consonants are very complex. The most common way to concatenate consonants is to remove the right-most portion of the first consonant and physically attach it to the second consonant (e.g., s; + t; = st; ; [; + ! = [!). However, there are other ways of joining consonants (e.g., ! + ! = ù ; d + v; = è). All of these methods are relatively transparent; both consonantal forms are easily visible. Other complex akshara are more opaque; their components are not easily visible. For example, whenever r /r/ is the first consonant in a complex akshara, it is represented by a curved line over the second consonant (e.g., r + d = d* ; r + t; = t;*). Whenever r /r/ is the second consonant, it is depicted as either one or two diagonal lines (p; + r = p;> ; k: + r = k>: ; ! + r = !M ; # + r = #M). Finally, some complex akshara are very opaque and need to be memorized (e.g., k: + {; = Z; ; t; + t; = T; ; t; + r = F;; d + d = ä). Second, complex akshara are often nonlinear. For example, in the akshara t;;* (r + t; + a;), the first phoneme (/r/) is found in the upper-right, the second phoneme (/t/) is found in on the left, and the third phoneme (/a/) is found in the lower right.

Another difficulty with learning complex akshara is that, although complex akshara as a type is common, an individual complex akshara is rare. Patel, Bapi, and Nag (2013) identified 702 different akshara in texts for children in Grades 1-5. Although 285 of those akshara (40%) were complex akshara, only 60 of those complex akshara occurred more than ten times. Of the 50 most common akshara, only three were complex akshara (Nag, 2014a). Therefore, although complex akshara recognition is very important for text comprehension, texts may not provide enough exposure to a given complex akshara for a child to be able to easily recognize it. Furthermore, instructors report that a very small percentage of complex akshara are explicitly taught (Nag, 2014a; Nag & Sircar, 2008; P. G. Patel, 2004). Thus, instruction that explicitly teaches complex akshara may be beneficial.[2]

Complex akshara are particularly difficult to learn, a result demonstrated in many alphasyllabaries (Telugu: Vasanta, 2004, Bengali: Nag & Sircar, 2008, Malayalam: Tiwari, Nair, & Krishnan, 2011, Kannada: Nag, 2007; Nag, Treiman, & Snowling, 2010; and Joshi, 2013). For example, Nag (2007) tested children between grades one

[2] The research cited here was not done with Hindi, but rather with other languages that use alphasyllabic orthographies. However, to the best of our knowledge, a similar analysis has not been done with Hindi. We are presuming that distributional properties are relatively similar across alphasyllabic orthographies and that instructional principles are similar across India.

and four learning Kannada on their knowledge of 20 akshara: eight simple consonantal akshara, one simple vowel akshara, five CV akshara, and six complex akshara. Children in Grade 1 were 71.8% correct at naming simple consonantal akshara but were near-zero on the other akshara types. By Grade 2, children were nearly perfect at naming simple consonantal akshara, but continued to struggle with the other akshara types. Children in Grade 4 were only 80% correct at naming the akshara overall. More specifically, although they were nearly perfect at naming simple consonantal akshara, they were on average only 72.5% correct at naming CV akshara, and 55.2% correct at naming complex akshara. Similarly, Tiwari et al. (2011) studied children in Grade 3 learning Malayalam and found that though they had a strong grasp on simple akshara, they found CV akshara more difficult, and complex akshara extremely difficult. Out of the six complex akshara they were tested on, children in the 25th percentile got all of them wrong, the median score was three, and children in the 75th percentile got only 4.75 correct. Not only is akshara recognition difficult, but so is production. Both good and poor spellers in Grades 4-5 learning Kannada had more difficulty spelling words containing complex akshara than words containing CV akshara, which in turn were more difficult than words containing only simple akshara. Furthermore, the difference between the good and poor spellers was largest on words containing CV and complex akshara (Nag et al., 2010).

Problems with akshara reading can cause reading difficulties. Nag and Snowling (2012) found that, after controlling for non-verbal IQ, akshara knowledge accounted for 50.1% of the variation in reading accuracy and 26.7% of the variance in reading rate in 4th-6th grade children. Thus, helping children with their akshara knowledge should benefit reading overall.

Phonological Challenges

In addition to orthographic challenges, Hindi also presents some phonological challenges. First, it contains many similar phonemes that contrast only in terms of place of articulation or aspiration (e.g., d /d̪/ and # /ɖ/ vary by place of articulation; k: /k/ and K; /k^{h}/ vary by aspiration).

Second, although the name “alphasyllabary” suggests that graphs map onto syllables (a misunderstanding of the term, see Bright, 1992; Bright, 2000; Nag, 2017; Salomon, 2000), in reality the relationship between graphs and phonological units is not that straightforward. In fact, because akshara do not map onto syllables[3], some

[3] A syllable is defined as a sound or set of sounds that contain a vocalic nucleus and may contain consonants in either the onset or coda position. Because akshara cannot represent consonants in the coda position (with the

scholars have suggested that the term "alphasyllabary" is misleading and prefer the term "abugida" (Daniels, 1990; Share & Daniels, 2016). Complex akshara can either represent consonantal blends or two adjacent complex akshara that cross a syllabic boundary. For example, in the word vy;;y;;m; /wja.yam/ (exercise), the complex akshara vy;; /wja/ represents a consonantal blend. In contrast, in the word b;t;*n; /bər.ʈən/ (pan; kitchen utensil), the complex akshara t;∗ /r.ʈə/ represents two consonants that cross a syllabic boundary. Complex akshara that cross a syllabic boundary are more difficult to learn than complex akshara that represent a blend (Nag, 2014a).

Mobile Game

Because teachers dedicate little instructional time to explicitly teaching complex akshara and akshara recognition is an important predictor of reading ability, supplementing classroom instruction with mobile games that focus on complex akshara may be beneficial. Mobile games have been shown to improve literacy outcomes among elementary school students (Jere-Folotiya et al., 2014; Kam, Kumar, Jain, Mathur, & Canny, 2009). We need to know if such mobile games can effectively increase akshara knowledge. In this study, we test a mobile game that teaches children complex akshara both in isolation and in word contexts. The game also seeks to improve orthographic and phonological knowledge more generally by including close orthographic and phonological foils.

The mobile game format has several benefits for use in educational interventions. First, it allows students to progress at their own pace so that every student is appropriately challenged. Second, it allows students to practice language skills in informal, non-classroom environments during their fragmented time. Third, the format is engaging and motivating for students (Perrotta, Featherstone, Aston, & Houghton, 2013).

Spacing Manipulation

The goal of this study was not just to determine if a mobile game can bolster complex akshara knowledge, but also to determine the optimal design for such a game. We compared two versions of the game to identify how stimuli should be spaced to optimize learning. In one version of the game, problems[4] about the same akshara were grouped together (massed). In the other version, problems about the same akshara were presented in a more distributed manner (distributed). Previous research has shown that spacing stimuli leads to slower initial learning,

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exception of nasals), they either represent syllables or demi-syllables. For example, the word m;uz;e /mudʒʰe/ has two syllables, each of which is represented by an akshara. In contrast, the word g;>;m; /gram/ contains one syllable that is represented by two akshara.

[4] See the section on Game Design below for descriptions of the problems.

but better long-term retention (Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Underwood, 1961). The experiment realizes the spacing manipulation slightly differently than has been done previously. Most studies utilizing a spacing manipulation repeat the same or very similar problems at different intervals. In contrast, in the present study, the same akshara are presented in different contexts. Specifically, in the massed version, students learn an isolated akshara and then immediately practice it in a word context. In the distributed version, students learn 10 isolated akshara and then practice all of them in word contexts.

In the massed version, students are exposed to the same akshara twice in a row. In contrast, in the distributed version, students are exposed to a given akshara in a more distributed manner. Thus, the schedule of akshara exposure is similar to the traditional spacing manipulation. Furthermore, the massed version of the game is easier because students know that the akshara they just learned will be in the word. Therefore, students do not need to rely solely on phonology-akshara correspondences to spell the word; they already know what one of the correct answers is and they need to only fill in the remaining akshara. Furthermore, at least in the words with only one complex akshara (which is true of all the words in the earlier levels), students can automatically eliminate all of the complex akshara foils. Normally when children are spelling words, they do not know which complex akshara is in the word and have to rely purely on phonology-akshara correspondences. Thus, the distributed version is more authentic and is better training students to use phonology-akshara correspondences. Because the distributed version requires students to spell words from scratch, it may take longer to play this version but lead to better learning outcomes. This prediction is in line with the literature on desirable difficulties (McDaniel & Butler, 2011).

However, the massed version does have one advantage over the distributed version: because the isolated akshara and the akshara-in-word-context are shown consecutively, students can better understand how the akshara they learned functions in a word context. In the distributed version, this relationship is harder to discern. Thus, it is possible that the additional difficulties created by the distributed version will not be desirable in this instance (McDaniel & Butler, 2011).

Overview

The efficacy of a mobile game that teaches Hindi decoding skills is measured using a pre-test, post-test format. Additionally, we looked at data collected by the game itself for evidence of improvement. There are two versions of the game that vary in the order of their stimulus presentation. The two groups that play the game are

compared to an unseen control group[5]. The game is tested with 4th grade children in Bangalore, India. All of our participants were second language learners of Hindi.

Methods

Game Design

The game consisted of two types of problems. In the first type of problem, a complex akshara was shown and the children had to select the simple akshara of which it was composed (i.e., akshara decomposition, see Figure 1). In the second type of problem, the children would hear a word and have to spell it using the akshara provided (i.e., spelling, see Figure 2). Each level consisted of 10 akshara decomposition problems and 10 spelling problems. The spelling problems contained the akshara taught through akshara decomposition (e.g., after learning the complex akshara g;>; /gra/, children had to spell the word g;>;m; /gram/ [village]). To pass a level, the child had to finish all 20 problems before time ran out and earn a sufficient number of points.

Akshara decomposition. A complex akshara was displayed and the child had to choose the simple akshara of which it was composed in the correct order from the options at the bottom of the screen. The number of simple akshara options ranged from 7 to 16. Typically, the number of options increased as the child progressed through the game. The simple akshara options remained constant within a level and were displayed in the order of the *varnamala* (similar to alphabetic order in English). If the child was having trouble, there were two hint buttons that she could use. The first one color-coded the different parts of the akshara, making it easier to decompose. The second hint button would pronounce the akshara, so it was possible to hear which simple akshara it was composed of. The pronunciations were recorded by a native Hindi speaker. Three points were given for correct answers obtained without using any hint buttons, two points if one hint was used, and one point if both hints were used.

Spelling. The game played an audio recording of a word and displayed a picture that represented the meaning of the word. The words' pronunciations were recorded by a native Hindi speaker. The child had to spell the word using the akshara choices at the bottom of the screen. In the first level, there were 6-7 akshara choices for each word. After that, there were 8-10 akshara choices. The foils were designed to be orthographically and phonologically similar to the correct answers (see Figure 2). The child could listen to the word as many times as

[5] The students in the experimental groups were taken out of their classes to play the game. Care was taken so that students did not miss the same school subject repeatedly. Therefore, the experimental group did spend more time in Hindi instruction (Hindi class + playing the game) than did the control group.

necessary without any penalties. If a child was struggling, she could press the help button, which would delete two of the foils at random. Two points were given for correct answers obtained without using a hint button and one point was given if the hint button was used.

All the words were chosen to be age-appropriate for the children. There are two popular curricula in India, the Central Board of Secondary Education (CBSE) and the Indian Certificate of Secondary Education (ICSE). All of the words were chosen from either CBSE or ICSE 3rd-5th standard textbooks. [6]

The game was designed to build both orthographic and phonological knowledge. In the akshara decomposition problems, the children had to select the constituent akshara. Because the children know how to pronounce the simple akshara, they should be able to blend to determine the pronunciation of the complex akshara. One of the hint buttons would also pronounce the akshara for them if they were struggling. The other hint button would break down the complex akshara for them visually. In the spelling problems, the children had to spell an auditorily presented word, thus building phonology-to-orthography connections. Furthermore, close orthographic and phonological foils were included.

Game play. At the top of the screen were two bars, one that counted down the amount of time remaining and another that counted how many points had been earned. The children were given 4 minutes to complete levels 1-15 and 3.5 minutes to complete levels 16-30. The children needed to earn 40 points to pass levels 1-15 and 45 points to pass levels 16-30. If the child ran out of time during a level, a message would show on the screen stating that time has run out and the level would re-start. If the child finished the level within the time limit but did not earn enough points to move onto the next level, a message would be displayed explaining this and then the level would restart. If the child successfully completed a level, a congratulatory message would be shown and then the next level would begin. The top of the screen contained 30 stars. One star was colored in for every level successfully completed.

Levels. The first level consisted of very high frequency words that the children should be familiar with (e.g., m;;t;; [mother]). All of the words contained CV akshara but did not contain complex akshara (diacritics included: (/a/, /i/, /i:/, /u:/, /e/, /o/). In the spelling problems, there were only 6-7 akshara choices. Levels two and three also contained CV akshara and no complex akshara. They were designed such that each of the following diacritics (/a/, /i/, /i:/, /u/, /u:/, /e/, /ai/, /o/, /ou/, and nasal) was taught within one problem. In levels 4-28, every word

[6] All the words on the reading and spelling assessments were selected from these textbooks as well.

contained one complex akshara. In levels 29 and 30, every word contained two complex akshara. Only one of those complex akshara was practiced in the akshara decomposition problem, but the unpracticed complex akshara was taught in a previous level. The words in levels 2-30 were of mixed frequency (e.g. of high frequency word: तुम्हें [you]; e.g. of low frequency word: सुपाच्च [easily digestible]). The game kept a log of all activity that could be analyzed at a later time.

Game versions. There were two versions of the game. In the massed version, the akshara decomposition and spelling problems would alternate in every level. Therefore, right after the children learned to decompose an akshara, they would practice spelling a word that contained that akshara. In the distributed version, the children would do all 10 akshara decomposition problems and then all 10 spelling problems. Other than the order of the stimulus presentation, the two games were identical.

Game Development

The mobile game was programmed using e-Chimera, a visual end-user programming environment that can design experiments for mobile devices (Luo, Head, Schneider, & Wang, 2014). The e-Chimera environment offers end-to-end support for the design, testing, and deployment of mobile experiments for psychology, cognitive science, and social science researchers.

After the interaction logic is defined via drag-and-drop interactions in the e-Chimera IDE, it is translated into domain-specific language (DSL) automatically. The DSL can be extended to support customized behavior. In the case of Hindi mobile game, DSL Scripting was used to create a customized progress bar and customized logic to check if a child's spelling is correct. After generating the DSL scripts, the e-Chimera IDE bundles together all codes, dependencies, and required resources into an executable mobile app for the target platform such as iOS, Android, or Windows. The game was played on Android mobile phones.

Pre and Post-tests

Pre and post-tests included measures of the children's Hindi akshara recognition, reading, spelling, and math abilities and their knowledge of vocabulary and ligaturing rules. Non-verbal IQ was measured at pre-test only. The testing took approximately one hour per child.

Non-verbal IQ. The matrix reasoning subtest from the Wechsler abbreviated scale of intelligence (WASI) was administered at pre-test only (Wechsler, 1999).

Akshara recognition. Children were presented with 20 akshara (nine simple, six CV, five complex) and were asked to read them aloud as quickly as possible (Nag, 2014c; see Appendix A). The children were given six akshara as practice items before the test began. The task was recorded to allow a second experimenter to check the scoring.

Word reading. The children were asked to read 48 words, presented in six lists of eight words each. The first two lists consisted of words that did not contain complex akshara. The words in the first list were composed of simple akshara and were not taught in the game (i.e., simple list). The words in the second list all had two CV akshara and were not taught in the game (i.e., CV list). The words in the final four lists all had one complex akshara and tested differing levels of transfer. The words in the third list were taught between levels 4 and 20[7] in the game (i.e., learned list). The words in the fourth list were not taught in the game, but the complex akshara within them was taught between levels 4 and 20 in the game (e.g., नष्ट, wherein ष्ट was taught in the game; i.e., near transfer list). The words in the fifth list were not taught in the game and their full complex akshara was also not taught in the game. However, the consonants within the complex akshara were taught between levels 4 and 20 in the game, but paired with a different vowel (e.g., चन्दा, wherein although न्दा was never taught, न्द was taught; i.e., medium transfer list). The words in the sixth list were not taught in the game, and the consonants within the complex akshara were never taught in the game (e.g., अग्नि, wherein ग्न or ग्नि or any other ग्न +V was never taught; i.e., far transfer list) (see Appendix B). The children were given unlimited time to read the words. If a child got a score of zero on five consecutive words within one list, the testing of that list was discontinued. Three practice items were given before the testing began. The task was recorded to allow a second experimenter to check the scoring.

Spelling. The children were asked to spell 30 words. Six types of words were presented from the same categories described in the word reading section (i.e., simple, CV, learned, near transfer, medium transfer, and far transfer) (see Appendix C). The lists were presented in an interspersed manner; the first word from each list was

[7] Levels 1-3 were not included because those levels did not contain complex akshara. We only went up to level 20 because we assumed that most students would reach that level by the end of the study.

presented, then the second word from each list, etc. If the child got a score of zero on three consecutive words from one list, the remaining words from that list were not administered.

Akshara construction. The akshara construction assessment measured students' knowledge of ligaturing rules and their ability to apply those rules in novel contexts. The children were introduced to a "made-up" akshara and were told to "pretend that it makes the /l/ sound". They were also told that "it can be combined with matras[8] and other Hindi akshara that you know". The children then practiced drawing it in isolation, combining it with vowel diacritics, and combining it with other akshara to make complex akshara. After the practice session, they were given six akshara construction problems: two of them were in the CV pattern (/la/, /lu:/), three were in the CCə pattern (/klə/, /blə/, /plə/), and one was in the CCV pattern (/gle/).

Vocabulary. The children were asked to define 24 Hindi words. 1/3 of the words were taught during the first 20 levels of the game, 1/3 of the words were morphologically related to words taught during the first 20 levels of the game, and 1/3 of words were unrelated to the game (see Appendix D). The words unrelated to the game were selected from Nag (2014b). Definitions given in either Hindi or English were accepted, as were English translations. Before testing began, the experimenter demonstrated one item and then had the child practice with two items. The task was recorded to allow a second experimenter to check the scoring.

Math. The Math Fluency subtest from the Woodcock-Johnson was administered (Woodcock, McGrew, & Mather, 2001). The children had three minutes to complete as many simple arithmetic problems (i.e., addition, subtraction, multiplication) as possible. The score consisted of the number of correct answers. This test was included to see whether the gains from the intervention were specific to Hindi literacy skills. If the intervention group improved more than the control group on the math assessment (a skill the game was not teaching), that would suggest that the improvements resulted from greater interaction with the experimenters. If not, that would suggest that the other gains resulted from the game itself.

Participants

The participants were all in the 4th standard at a large all-girls[9] private school in Bangalore, Karnataka, India. We chose to work with 4th grade students because Nag (2007) demonstrated that students of this age have generally mastered simple akshara, but still struggle with complex akshara. Because the study was conducted at a

[8] "Matra" is the Hindi word for "vowel diacritic".
[9] In India, many schools are gender-segregated.

private school, the participants were generally from middle and upper-middle class families (with a very small percentage from lower middle class families). The state language of Karnataka is Kannada. However, Bangalore is a large, cosmopolitan city with immigrant families from all over India, so the students speak a wide variety of languages at home. The majority of the students spoke South Indian languages at home: 34, 19, 16, and 14 students spoke Tamil, Telugu, Malayalam, and Kannada, respectively. Other languages spoken included Punjabi, Oriya, Bengali, Katchhi, Konkani, Gujrati, English, Rajasthani, and Coorgi. The content areas are all taught in English so all of the students are fluent in English. The students have to select two additional languages to study. For their first additional language, they can choose between Hindi and Kannada. For their second additional language, they can choose between Hindi, Kannada, and Sanskrit. More instructional time is dedicated to their first than to their second additional language. All of the children in our sample had chosen Hindi as their first additional language. Children who spoke Hindi or a language that was similar to Hindi (e.g., Marathi, Urdu) at home were excluded.

A total of 122 children were pre-tested. If a child showed very low Hindi literacy skills (did not know even the simple akshara) pre-testing was discontinued because the game would be too challenging for her. 108 children (age range: 8.35-10.18 years, mean age= 9.26 years, SD= 0.37 years) had high enough pre-test scores to continue with the study; specifically, their akshara recognition, reading, and spelling scores ranged from 6—20, 2—40.5, and 0—17.5, respectively. 36 of them played the massed version of the game, 36 played the distributed version, and 36 were in an unseen control group. The three groups were selected to match as closely as possible on spelling pre-test scores, with no significant differences on the other pre-test measures. Five children were dropped because they went on vacation during the study or elected to discontinue with the study.

The study was approved by the University of Pittsburgh IRB and followed the ethical guidelines of The Promise Foundation.

Schedule

The pre-testing was conducted over a period of 2.5 weeks. The intervention was conducted over the next four weeks. Children were seen in groups of nine and each group was seen for a total of 12 sessions, 25 minutes long each. Each child played the game at her own pace. Twenty-eight children finished the entire game within the 12 sessions; the minimum number of sessions it took to finish the game was six. Of the 39 children who did not finish the game, 1 student was seen for nine session, 8 students were seen for ten sessions, and 12 students were seen for eleven sessions due to absences; the remaining 18 students were seen for all twelve sessions. The fewest levels

successfully completed by a student was 14 levels. The post-testing was done approximately 2 weeks after the intervention. The children who finished the game early were post-tested first (along with the children from the unseen control group with the highest scores) to keep the time between completing the intervention and the post-test approximately constant across all children.

Results

Pre and Post-tests

Non-verbal IQ. There were no statistically significant differences across the three groups in terms of non-verbal IQ, all *p*s > .5 (see Table 2).

Akshara recognition. The akshara recognition data (see Table 3) were analyzed using a logit linear mixed effects model[10]. Although ideally the model would have included a three-way interaction[11] among akshara type, experimental group, and time (pre-test/post-test), this model did not converge, likely because participants were nearly at ceiling on the simple akshara at post-test and logit models become unstable for proportions near 1 or 0. Therefore, it included akshara type and the interaction between experimental group and time. It also included the following random effects: 1) random intercept for participants; 2) the effect of akshara type (simple as compared to CV and complex) to vary by participants; and 3) random intercept for items.

Orthogonal contrasts were used to compare akshara type. The first contrast compared simple and CV akshara to complex akshara and the second contrast compared simple and CV akshara to each other. Orthogonal contrasts were also used to assess the effect of experimental group. The first contrast compared the control group to the average of both experimental groups. The second contrast compared the two experimental groups (massed and distributed) to each other[12].

[10] All models were fit in R using the lme4 package version 1.1-12 (Bates, Maechler, Bolker, & Walker, 2015).
[11] When we say that the model included an interaction, the model also included lower level interactions and main effects. For example, if the model includes a three-way interaction, it also includes all three two-way interactions and all three main effects. When the model includes a two-way interaction, it also includes both main effects.
[12] The same orthogonal contrasts were used to compare the three groups in all analyses. For the sake of brevity, we will not explain these orthogonal contrasts from now on.

Participants performed better on the simple akshara than on the CV and complex akshara, z = 7.513, p < .001. The odds[13] of answering a simple akshara problem correctly were 83.263 times higher than the odds of answering a CV or complex akshara problem correctly.

Participants improved from pre-test to post-test, z = 6.750, p < .001. The experimental groups performed better than the control group, z = 2.060, p =.039. Both of these main effects were qualified by an interaction between time and experimental group, z = 3.030, p = .002. This interaction is driven by the fact that participants in the control group did not improve from pre-test to post-test, z = 1.624, p = .104, but participants in the experimental groups did, z = 8.849, p < .001. For participants in the experimental groups, the odds of correctly recognizing an akshara on the post-test were 2.433 times higher than the odds of correctly recognizing an akshara on the pre-test.

Word reading. The reading data (see Table 4) were analyzed using logit linear mixed effects models. The models included a three-way interaction between word type, experimental group, and time (pre-test/post-test) as well as the following random effects: 1) random intercept for participants; 2) the effect of word type to vary by participants; and 3) random intercept for items.

To restrict the number of contrasts to a manageable amount, the model collapsed across some of the word types. Specifically, the "simple" and "CV" categories were collapsed into a "no complex akshara" category, the "learned" and "near transfer" categories were collapsed into a "learned complex akshara" category, and the "medium transfer" and "far transfer" categories were collapsed into a "transfer complex akshara" category. Orthogonal contrasts were used to assess the effect of word type. The first contrast compared the "no complex akshara" category to the average of the "learned complex akshara" and "transfer complex akshara" categories. Thus, this contrast compared words that did and did not contain complex akshara. The second contrast compared the "learned complex akshara" and "transfer complex akshara" categories, thus measuring the degree of transfer.

The data were scored in the following way: if the participant read the word correctly, she received a score of 1. For words containing complex akshara, if she read the complex akshara correctly but made a mistake elsewhere in the word, she received a score of 0.5. For words in the CV category, if she read both CV akshara correctly but made a mistake elsewhere in the word, she received a score of 0.5. Scores of 0.5 were not possible for words in the simple category because all of the akshara in the words were simple akshara; there was not a particular

[13] The model parameter estimates are in log odds. The odds are obtained by back-transforming the parameter estimates from the model.

target akshara. All other readings received a score of 0. Because binomial models only accept scores of 1 or 0, two scoring criteria were used. In the lenient scoring criterion, scores of 0.5 were scored as 1. In the strict scoring criterion, scores of 0.5 were scored as 0.

Lenient scoring criteria. Participants improved from pre-test to post-test, z = 14.198, $p < .001$. Participants were more accurate on words that did not contain complex akshara than on words that did contain complex akshara, z = 3.226, $p = .001$. These main effects were qualified by two interactions. First, there was an interaction between word type (contains complex akshara/does not contain complex akshara) and experimental group (massed/distributed), z = -2.023, $p = .043$. The difference between words with and without complex akshara was larger for the massed group. There was also an interaction between word type (learned complex akshara/transfer complex akshara) and time (pre/post), z = 3.098, $p = .002$. There was more improvement on the learned complex akshara than on the transfer complex akshara.

Importantly, there was a significant three-way interaction among experimental group (control/experimental), word type (no complex akshara/complex akshara), and time, z = -2.034, $p = 0.042$. Post-hoc[14] analyses were conducted to better understand this three-way interaction. At pre-test, there was no difference between the control and experimental groups on words without complex akshara, z = 1.263, $p = .207$, nor on words with complex akshara, z = 0.879, $p = .379$. At post-test, there was still no difference between the groups on words without complex akshara, z = 0.096, $p = .923$. But, the experimental groups marginally outperformed the control group on words with complex akshara, z = 1.688, $p = .092$. At post-test, the odds of the experimental groups correctly reading a word with a complex akshara were 1.491 times higher than the odds of the control group correctly reading a word with a complex akshara. To summarize, by post-test, the experimental groups outperformed the control group on words containing complex akshara, the words the game was training them on.

Strict scoring criteria. The results using the strict scoring criteria were very similar. Participants improved from pre-test to post-test, z = 13.800, $p < .001$. Participants were more accurate on words that did not contain complex akshara than on words that did contain complex akshara, z = 4.359, $p < .001$. These main effects were qualified an interaction: There was an interaction between word type (learned complex akshara/transfer complex

[14] All post-hoc analyses were conducted using the same linear mixed effects model but with fewer variables and a subset of the data. For example, here the time and word type variables were removed and separate analyses were conducted for pre-test words with complex akshara, pre-test words without complex akshara, post-test words with complex akshara, and post-test words without complex akshara.

akshara) and time (pre/post), z = 3.167, p = .001. There was more improvement on the learned complex akshara than on the transfer complex akshara.

The three-way interaction among word type (contains complex akshara/does not contain complex akshara), time (pre/post), and group (control/experimental) that was significant with the lenient scoring criteria was not significant with the strict scoring criteria, although the effects were in the same direction, z = -1.599, p = .110. However, because this interaction was significant with the lenient scoring criteria, we performed the post-hoc analyses with the strict scoring criteria. The results of the post-hoc analyses closely mirror those done with the lenient scoring criteria. At pre-test, there was no difference between the control and experimental groups on words without complex akshara, z = 1.122, p = .262, nor on words with complex akshara, z = 1.261, p = .207. At post-test, there was still no difference between the groups on words without complex akshara, z = 0.032, p = .975. However, the experimental groups marginally outperformed the control group on words with complex akshara, z = 1.709, p = .087.

Summary. In summary, the control and experimental groups were matched at pre-test. However, at post-test, the experimental groups outperformed the control group on words that contained complex akshara. This was the word type we were expecting to see the most gains in because words with complex akshara are more difficult and the game specifically focuses on them. This result is more clearly seen with the lenient scoring criteria than the strict scoring criteria. Because the lenient scoring criteria gives points for pronouncing the complex akshara correctly, this finding suggests that participants in the experimental groups made large gains in pronouncing the complex akshara correctly but may have continued to make mistakes elsewhere in the word. For example, students would confuse dental/retroflex consonantal pairs and unaspirated/aspirated consonantal pairs.

Spelling. The spelling data (see Table 5) were analyzed using a logit linear mixed effects model. The model included a three-way interaction among word type, experimental group, and time (pre-test/post-test) as well as the following random effects: 1) random intercept for participants and 2) random intercept for items. For the word type variable, we used the same orthogonal contrasts that we used in the reading analyses. We also used lenient and strict scoring criteria in the same way we did for the reading analyses.

Lenient scoring criteria. The results showed that there was improvement from pre-test to post-test, z = 12.546, p < .001. Accuracy was affected by word type: participants performed better on the words that did not contain complex akshara than on words that did contain complex akshara (z = 6.568, p < .001) and participants

performed better on learned complex akshara items than on transfer complex akshara items (z = 2.343, p = .019). There was also an interaction between test and word type (learned complex akshara/transfer complex akshara), z = -2.470, p = .014. Participants showed more improvement on the transfer complex akshara items than on the learned complex akshara items. [15]

Importantly, the overall degree of improvement was greater for participants in the experimental groups than for participants in the control group, z = 2.312, p = .021. This interaction was qualified by a three-way interaction among time, experimental group (control/experimental), and word type (no complex akshara/complex akshara), z = -2.800, p = .005. Post-hoc analyses were conducted to better understand this interaction. At pre-test, there was no difference between the control and experimental groups on words without complex akshara, z = 1.128, p = .259, nor on words with complex akshara, z = -0.811, p = .417. At post-test, there was still no difference between the groups on words without complex akshara, z = 0.423, p = .672. But, the experimental groups marginally outperformed the control group on words with complex akshara, z = 1.668, p = .095. At post-test, the odds of the experimental groups correctly spelling a word with a complex akshara were 1.992 times higher than the odds of the control group correctly spelling a word with a complex akshara. To summarize, by post-test, the experimental groups outperformed the control group on words containing complex akshara, both with the words the game was training them on and untaught words.

Strict scoring criteria. The model with the strict scoring criteria did not converge because of nearly floor effects on the words with transfer complex akshara (mean = 0.062). The words with transfer complex akshara may have been very challenging because they contained very rare complex akshara.

Akshara construction. The akshara construction data (see Table 6) were analyzed using a logit linear mixed effects model. The model included an interaction between experimental group and test (pre-test/post-test) as well as random intercepts for both participants and items. There was a main effect of test, with participants improving from pre-test to post-test, z = 7.965, p < .001. There were no effects of group nor group by test interactions, all ps > .38. Therefore, no benefits of the game were seen on the akshara construction test.

Vocabulary. The vocabulary data (see Table 7) were scored on scale of 0-3. Cross-rater agreement on scoring was high, kappa = 0.98. Because binomial linear mixed effects models require items to be scored as

[15] Although the model did not converge, the relative gradient was equal to 0.001. A relative gradient of 0.001 or less indicates sufficient convergence.

correct/incorrect, these data were transformed using strict and lenient scoring criteria. For the strict criteria, only items scored as a '3' were marked correct. For the lenient criteria, items scored as '1-3' were marked correct.

The vocabulary data were analyzed using two logit linear mixed effects models (one for strict coding, one for lenient coding). The models included three-way interactions among word type, experimental group, and test (pre-test/post-test) as well as the following random effects: 1) random intercept for participants; 2) the effect of word type to vary by participants[16]; and 3) random intercept for items. Orthogonal contrasts were used to assess the effect of word type. The first contrast compared the "words unrelated to the game" category to the average of the "words in game" and "words morphologically related to those in game" categories. Thus, this contrast compared words related and unrelated to those in the game. The second contrast compared the "words in game" and "words morphologically related to those in game" categories, thus measuring the degree of transfer.

The data showed that participants improved from pre-test to post-test (strict: $z = 6.254$, $p < .001$; lenient: $z = 6.592$, $p < .001$). The participants performed more poorly on words that were related to the game than words unrelated to the game (strict: $z = -2.313$, $p = .021$; lenient: $z = -2.669$; $p = .008$). This effect suggests that the words related to the game were more difficult than words unrelated to the game. Surprisingly, the participants also showed more improvement on words unrelated to the game than those related to the game (strict: $z = -2.459$, $p = .014$; lenient: $z = -2.272$, $p = .023$). There was no effect of, nor interaction with, experimental group. Therefore, there is no evidence that the game improved students' vocabulary knowledge.

Math. The descriptive statistics for the math data are displayed in Table 8. Because the math assessment required students to complete as many math problems as possible in a set amount of time, the most appropriate model to analyze these data is the Poisson distribution. The data were analyzed using a Poisson general linear model that included an interaction between experimental group and time (pre-test/post-test).

Participants improved from pre-test to post-test, $z = 13.842$, $p < .001$. Participants in the experimental groups performed marginally better than did participants in the control group, $z = 1.707$, $p = .088$. Importantly, there were no interactions between time and experimental group, ps $> .79$. As expected, the intervention groups did not improve on the math assessment to a greater degree than the control group did, suggesting that other improvements

[16] The strict scoring criteria analysis did not allow for the words morphologically related to those in the game/words in game contrast to vary by participants because that random slope explained very little variance.

made by the intervention groups are due to the game itself, and not due to their greater interaction with the experimenters.

Game Play

The pre and post-test data suggest that the game was beneficial and improved students' akshara recognition and their reading and spelling of words that contain complex akshara. Furthermore, there is no evidence that the two game versions yielded different outcomes. In addition to the pre and post-test data, the data from the game itself can be mined to look for differences between the game versions and evidence of learning. Note that this paper will focus only on the portion of game data that can provide insight into the efficacy of the game; analyses that examine error patterns within the game data can be found in Bhide, Luo, Vijay, Perfetti, Wang, and Nag (2019).

Group analyses.

Comparing game versions. There is evidence that the distributed version of the game was more difficult than the massed version of the game because it took longer to play. Students playing the massed version spent marginally less time on each level (M = 326.4s) than students playing the distributed version (M = 352.2s), t (65) = 1.9, p = .056.

The game tracked every touchscreen response that the participants made. These data were used to compare the two game versions and to look for evidence of learning. For every problem, the average number of touchscreen responses it took participants to arrive at the correct answer was calculated. First the data were cleaned to remove times in which participants quit in the middle of the problem (perhaps they quit the game because they had to go to class or the game quit in the middle of a problem because they had run out of time and had to re-start the level). Thus, the problems the participants had solved correctly remained. Then, the number of touchscreen responses it took participants to arrive at the correct answer was counted. Then, the average number of touchscreen responses it took to correctly answer each problem was calculated separately for the massed and distributed groups.

Touchscreen responses included selecting an akshara, de-selecting an akshara, re-playing the audio for the words, and asking for a hint. If a given participant did the same problem multiple times, all attempts were included. It is important to note that all participants completed the problems in the earlier levels, whereas fewer participants completed the problems in the higher levels. In the highest levels, the highest performing participants and participants in the massed group are over-represented. It is also important to note that this analysis cannot account for instances in which the students asked the experimenters for help.

For the akshara problems, there was no significant difference between the massed (mean = 4.365 touchscreen responses, SD = 5.566) and distributed (mean = 4.472 touchscreen responses, SD = 6.458) spacing groups, t (299) = 0.425, p = .671. However, for the word problems, participants in the distributed group (mean = 11.327 touchscreen responses, SD = 12.475) required, on average, significantly more touchscreen responses than did participants in the massed group (mean = 8.989 touchscreen responses, SD = 9.954), t (299) = 12.043, $p < .001$. Thus, the fact that students in the massed group played faster seems to be primarily driven by the word problems, not the akshara problems.

Evidence of learning. Often, the same or highly similar akshara decomposition problems repeated through the game. Participants required fewer touchscreen responses, on average, to respond to these repeated problems, providing evidence of learning. For example, participants struggled with T; in level 4, they took, on average, 10.2 touchscreen responses to get it correct. In levels 6 and 7, they encountered the akshara T;I, and took an average of 7.5 and 5.2 touchscreen responses to get it correct, respectively. This reduction is especially impressive because the akshara in level 4 does not have a vowel diacritic, so it takes a minimum of two touchscreen responses to get correct. The akshara in levels 6 and 7 does have a vowel diacritic, so it takes a minimum of three touchscreen responses to get correct. Another example is that participants struggled with the sF; akshara in level 6; on average they took 11.8 touchscreen responses to get it correct. When they encountered it again in level 16, they took an average of 3.9 touchscreen responses to get it correct.

Participant-centered analyses. The game data can also be used to find evidence of learning on a by-participant basis. The data were filtered to only include the first time a subject successfully completed a given item. The average number of touchscreen responses it took each subject to correctly answer the akshara and word problems in each level was then calculated. The average number of touchscreen responses was then correlated with the level number[17]. If the correlation is negative, this indicates that participants improved as they played the game. The average correlations for both akshara and word problems were significantly less than zero, indicating that participants did improve throughout the game (akshara: average r = -0.289, t (69) = -12.759, $p < .001$; words: average r = -0.073, t (69) = -2.010, p = .048). However, the magnitude of improvement was much larger for the akshara problems than the word problems, in fact the improvement on the word problems was negligible. This discrepancy could result from the fact that some akshara repeated throughout the game, whereas words never

[17] Only levels 4-30 were included because levels 1-3 did not contain complex akshara.

repeated. Furthermore, akshara are more similar to each other than are words, so insights gleaned from one akshara problem are more easily applicable to a future problem.

Discussion

Overall, the game improved students' akshara knowledge. This improvement was apparent in both the game data and the pre/post-test data. In terms of pre/post-tests, the benefit of the game was most apparent on the akshara recognition assessment. Students in the control group did not improve on this assessment from pre-test to post-test whereas students in the experimental groups showed significant improvement. There were also gains on the reading and spelling tasks, although they were not as robust as those with akshara recognition. Specifically, the game helped students read and spell words that contained complex akshara. Importantly, the game helped students with both learned and transfer items, suggesting that they are not simply memorizing the words taught in the game, but rather learning how to decode. On the reading assessment, improvement was more apparent when using the lenient scoring criteria than the strict scoring criteria, suggesting that participants were getting the complex akshara correct but making mistakes elsewhere in the word. In terms of game data, participants required fewer touchscreen responses to correctly answer problems as the game progressed. Furthermore, participants required fewer touchscreen responses on repeated problems, suggesting that they were remembering the correct answers and learning from their mistakes.

The experimental design used an unseen control group, rather than an active group that does a non-reading related activity. The experimental groups may perform better due to Hawthorne effects (Cook, 1962), specifically the experimental groups may do better because they feel more comfortable with the experimenters and they know they received the treatment and are expected to do better. The mathematical assessment, an assessment the game is not expected to improve, was included to look for the presence of Hawthorne effects. The students improved a great deal on this assessment, likely due to practice effects and because of their math classes in school. However, importantly, the experimental groups did not improve to a greater degree than the control group did on the mathematical assessment, suggesting that the improvements in Hindi are due to the game itself, and not due to Hawthorne effects.

Although the goal of the game was not to teach vocabulary, a vocabulary assessment was included to test for incidental vocabulary learning in the game. There were no intervention effects on the vocabulary assessment. This is likely because the children did not need to attend to word meanings to pass the levels, so they did not.

Furthermore, it may have been difficult to ascertain the exact definition of the word from the picture. Finally, the vocabulary assessment we used was quite challenging; participants were required to produce the correct definition. Perhaps a multiple-choice recognition assessment in which participants could use clues from the pictures to eliminate incorrect answers would have shown evidence of some vocabulary learning. There also were not any intervention effects on the akshara construction assessment, which was surprising because we did expect to see effects on this assessment. It is possible that there was not enough power to see intervention effects on the akshara construction assessment because there were only six items. Furthermore, ceiling level performance could have made it difficult to see significant effects.

It was interesting that, although the distributed version of the game was more difficult, it did not yield more gains on the post-tests. We expected the distributed version to be more beneficial because previous research has shown that spaced practice is generally more beneficial than massed practice (see Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Underwood, 1961 for review), including for learning spelling (Fishman, Keller, & Atkinson, 1968). Typically, in massed practice, the to-be-learned item is shown repeatedly, whereas in spaced practice, the to-be-learned item is shown in a more distributed fashion. The massed/distributed distinction in the present study is slightly different in that the game did not present the same item repeatedly, rather once the akshara was shown in isolation and later the akshara was shown in a word context. Nevertheless, we expected the distributed spacing to be beneficial. Furthermore, the massed version is theoretically easier because once you have learned an akshara, you know that akshara will be in the following word. Thus, you already know one of the correct answers. In the distributed version, you do not have this advantage. Analyses with the data extracted from game play demonstrated a massed advantage; students playing the massed version required fewer touchscreen responses to correctly answer the word problems. From the point of view of desirable difficulties (McDaniel & Butler, 2011), the distributed version should be more beneficial. Furthermore, students in the distributed version were less likely to finish all 30 levels in less than 12 sessions, so overall, they spent more time playing the game. Although, from a theoretical standpoint, we expected the distributed version to be more beneficial, this advantage was not borne out in the pre and post-test data.

It is possible that the distributed version was not beneficial because, although it was difficult, this difficulty was not desirable. McDaniel and Butler (2011) suggest that whether or not a difficulty is desirable depends on properties of the participants, materials, and criterial tasks. We believed that the difficulty created by the distributed

version would be desirable because one of the criterial tasks (spelling), required students to spell words based solely on phonology-akshara correspondences. Therefore, the type of processing required by the distributed version was more in line with the type of processing required on the spelling post-test. However, it is possible that our participants had trouble seeing the relationship between isolated complex akshara and how they function in word contexts. The fact that the distributed version obscured this relationship could have induced a difficulty that was not desirable. Thus, it seems that the massed version is both efficient and effective and should be used going forward. However, it is possible that for more skilled students who have a strong grasp on how complex akshara function in word contexts, the additional difficulty created by the distributed version will be beneficial. Thus, more research examining the interaction between spacing and ability is needed before a strong recommendation can be made for the massed version for all players.

Although the game was helpful, the pre and post-test data indicated that there were three areas in which students continued to struggle. First, students struggled with some of the vowels. For example, only 14% of students pronounced /tʃɛ/ correctly on the akshara recognition post-test. The /ɛ/ vowel may have been difficult because it has two possible pronunciations; it is pronounced as /ɛ/ in most contexts but as /əi/ when preceding a /j/ (Kachru, 2006).

Second, Hindi has many similar phonemes that vary only in aspiration or place of articulation. We expected the game to help students distinguish these similar-sounding phonemes because we used many close phonological foils in the word level of the game. However, the post-tests showed that phonological errors were still rampant. Specifically, students tended to use dental/alveolar forms when they should have used retroflex forms and they tended to use unaspirated forms when they should use aspirated forms. For example, on the spelling post-test, 88% of students spelled a word containing the /ɳ/ phoneme with /n/ and 66% of students spelled a word containing the /tʃ^{h}/ phoneme with /tʃ/. On the akshara recognition post-test, 67% of students pronounced /b^{h}i/ as /bi/. This pattern may reflect the frequencies of certain phonemes in Hindi; dental/alveolar form are more frequent than retroflex forms and unaspirated forms are more frequent than aspirated forms (Khan, Gupta, Rizvi, & Gupta, 1991).

The students' difficulties with aspiration and place of articulation contrasts suggest that the use of close phonological foils in the game was not sufficient to help students with these distinctions. Further, although the game included all vowel diacritics, students continued to struggle with some of the diacritics. It is unclear from these data if these problems are specific to second language learners, or if native Hindi speakers also struggle with these

aspects of Hindi. Nevertheless, future versions of the game may benefit from problems that focus on teaching children about challenging diacritics and helping them discriminate consonantal minimal pairs.

Finally, in this game, students simply needed to select the correct answer, they never needed to write it out. Recent work on akshara learning suggests that physically writing out akshara benefits learning in both children and adults because it allows for motor encoding (Bhide, 2018; Benny & Nag, 2018). Thus, the game could be improved by having students write the correct answers on the touchscreen[18]. Perhaps, by adding this feature to the game, even larger benefits would be seen on the spelling assessment.

One limitation of this study is that the participants were not representative of all possible players of this game. For example, this study was conducted at an all-girls school, so we were not able to include boys. Given that there are gender differences in reading interest and response to educational games (Kinzie & Joseph, 2008; Logan & Johnston, 2009), further research needs to be conducted with boys. Furthermore, this research was conducted with middle class students who likely have some access to touchscreen technology at home. More research needs to be done with students of lower SES, who may struggle with touchscreen technology. Finally, this study was conducted with second language learners of Hindi, who already understand the alphabetic principle in English. More research needs to be conducted with first language learners, who may not understand the principle of akshara-phonology mappings. However, first language learners may make fewer phonological errors (Mathur & Nag, 2018).

Despite these limitations, this study provided preliminary evidence that mobile technology can be harnessed to improve students' complex akshara recognition. However, we recognize that such technology may not be available in all classrooms. In such cases, educators can still give focused practice on complex akshara using paper-and pencil methods. Such practice may be beneficial because natural texts do not provide sufficient examples of a given complex akshara (Nag, 2014a; J. Patel et al., 2013).

[18] Note that although students could write the akshara on the touchscreen, it would be difficult for the technology to provide accuracy feedback to the children.

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Appendix A

Test of Akshara Recognition – Hindi (Nag, 2014)

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क	व	स्व
म	इ	त्रि
स	धॊ	चै
य	शु	स्ट्र
च	हॊ	स्थ
न	भि	व्य
आ	लु	

Appendix B

Stimuli on the Word Reading Assessment

Simple	शतक	नकल	अमर	बदन	सबक	अवसर	मतलब	लगभग
CV	मौका	घोड़ा	संदेश	दूसरा	तैरना	अकेला	खिड़की	नुकसान
Learned	ग्राम	मक्खन	डिब्बा	मिट्टी	महात्मा	अक्षरों	परिश्रम	घण्टियाँ
Near Transfer	नष्ट	y;ukt;	प्याज़	ज्यादा	निर्णय	सार्थक	सामान्य	पवित्रता
Medium Transfer	मुख्य	xv;et;	चन्दा	मुम्बई	बिल्कुल	वस्तुएँ	उन्होंने	पुल्लिंग
Far Transfer	अग्नि	अवश्य	दफ़्तर	सन्ध्या	अभ्यास	सम्मान	निर्भय	संस्कृत

Appendix C

Stimuli on the Spelling Assessment

Simple	फसल	कलम	शहद	अकसर	बचपन
CV	मुझे	बिजली	सैनिक	पूछना	समारोह
Learned	शब्द	उत्सव	दुश्मन	समुद्री	आक्रमण
Near Transfer	त्याग	g;upt;	उन्नति	विशेष्य	रम्भाना
Medium Transfer	उम्र	चर्चा	स्वीकार	सिक्किम	लोकप्रिय
Far Transfer	भ्रमण	लक्ष्मी	in;xc;y;	दुर्बल	इम्फाल

Appendix D

Stimuli on the Vocabulary Assessment

Unrelated to game	Learned in game	Morphologically related to words in game
घोड़ा	मूर्ख	घण्टी
खिड़की	टक्कर	हल्का सा
भूखा	रस्सी	प्यासा
खरीदा	सम्राट	स्त्री
डर	धक्का	रुलाया
गर्जना	आत्मकथा	छात्रों
छोटा	इन्द्रधनुष	दर्शकों
खतरनाक	नन्हाँ	स्नान करना

Table 1

Examples of different akshara types

Akshara Type	Akshara	Phonology
Simple Vowel	W	/u/
Simple Consonant	s;	/sə/
CV	s;u	/su/
Complex	st;u	/stu/

Note. The simple consonant typically represents a syllable, the consonant and an inherent schwa. However, depending on word context, the schwa may not be pronounced, so the simple consonant can represent a phoneme. See Bhide, Gadgil, Zelinsky, & Perfetti (2014) for more information about schwa deletion.

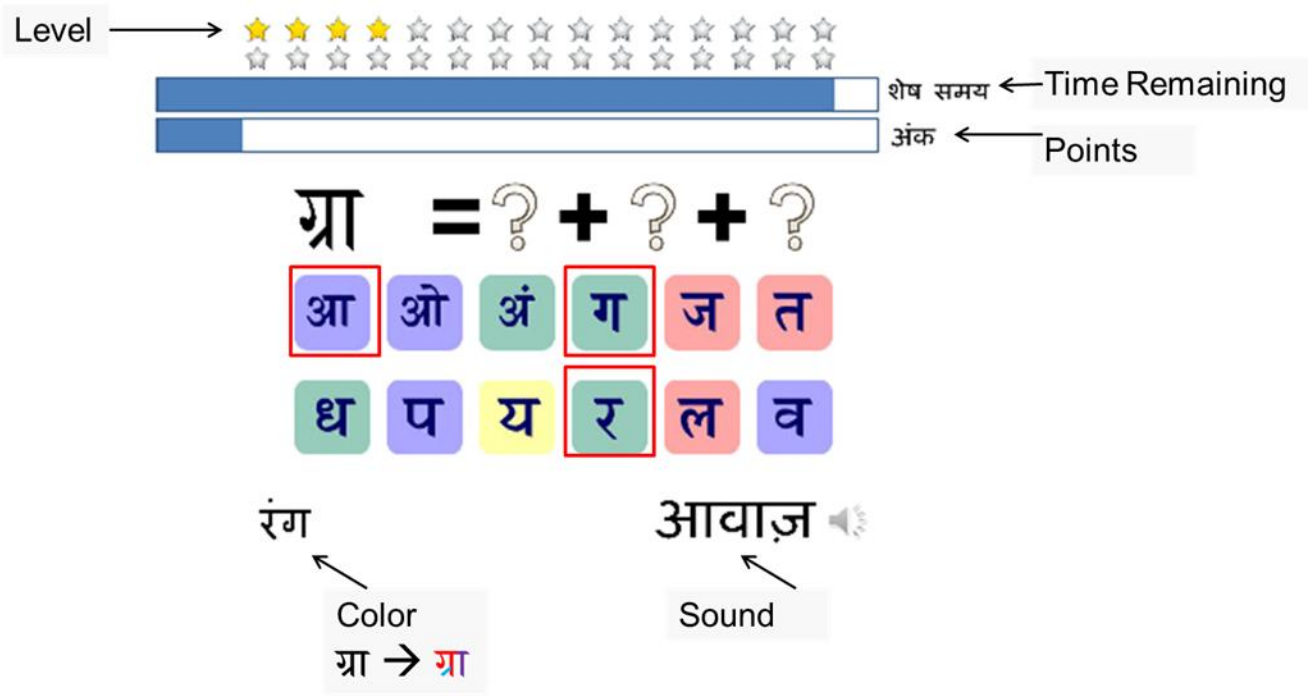

Figure 1. A screenshot of an akshara decomposition problem. The stars at the top show how many levels have been successfully completed. The stars were highly motivating for the children. The bars at the top display how much time is left in the level and how many points have been earned so far in the level. The complex akshara g;>; /gra/ is shown. The simple akshara options are below. The three correct ones have red boxes around them. The students needed to choose the akshara in the correct order to move on to the next problem. The two hint buttons, color and sound, are at the bottom.

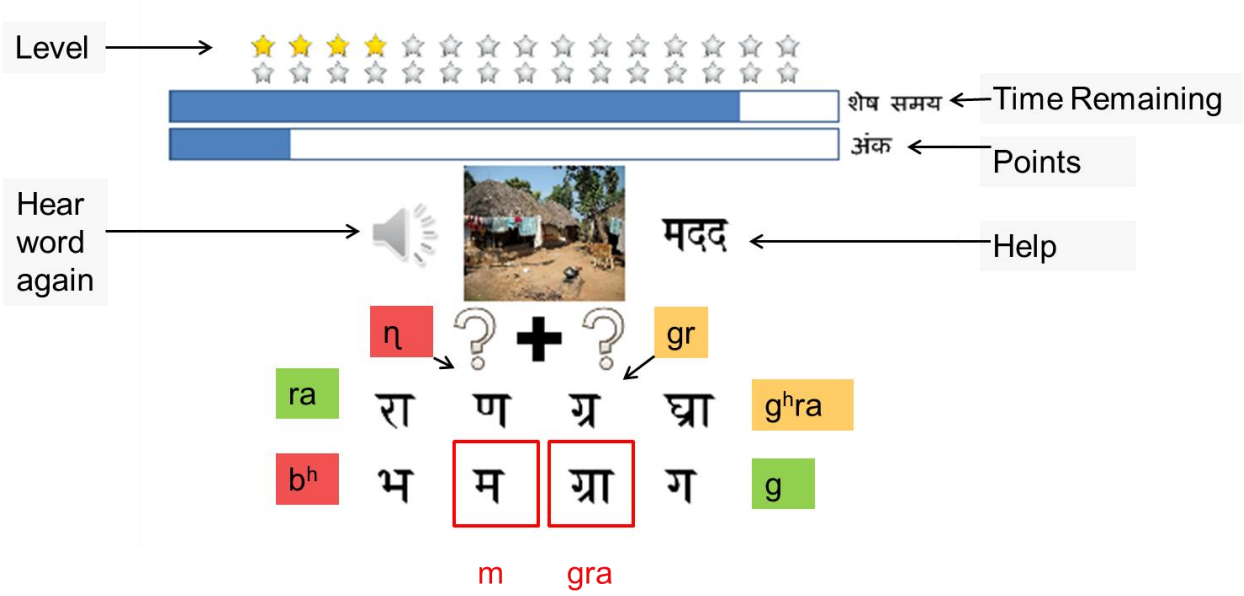

Figure 2. A screenshot of a spelling problem. Children would hear the word /gram/ (village). They could press the speaker to hear it again. The picture depicts the meaning of the word. All pictures were chosen to be age and culturally appropriate (e.g., modest dress, no alcohol, images depicted both Indian people and people of other races, pictures included images from a wide variety of religions including Hinduism and Christianity). If a child presses the "help" button, two foils are automatically removed. Children have to choose the correct akshara (the ones in red boxes) in the correct order to spell the word. Note that the complex akshara they just learned (/gra/) is in this word. We added color-coded labels to show how the akshara are pronounced. The orthographic foils are shown with red backgrounds, the phonological foils are shown with yellow backgrounds, and the split foils (one of the consonants in the complex akshara) are shown with green backgrounds. A few words also had combination foils (combining consonants from two different akshara into one akshara), but the problem displayed here did not.

Table 2

Mean (standard deviation) raw scores on the matrix reasoning assessment

Experimental Group	Score
Control	17.583 (6.447)
Massed	16.667 (7.119)
Distributed	17.111 (6.968)

Note. The students in the present study were 8.34 – 10.18 years old, with an average age of 9.26 years. The average scores for 8.34, 9.26, and 10.18 year old children are 15.5, 18, and 21, respectively (normed to a US population). Thus, the participants' non-verbal IQs were average for their age.

Table 3

Mean (standard deviation) accuracy on the akshara recognition test (in percents)

	Control		Massed		Distributed	
	Pre	Post	Pre	Post	Pre	Post
Simple	95.37 (9.71)	95.68 (9.31)	94.44 (9.78)	98.96 (3.29)	94.29 (15.33)	98.69 (3.63)
CV	46.3 (21.50)	50.93 (24.86)	46.88 (21.77)	57.29 (20.71)	55.71 (22.49)	59.8 (21.37)
Complex	31.11 (28.86)	35.56 (26.67)	36.25 (28.93)	53.13 (29.89)	34.29 (27.26)	51.18 (27.05)

Note. Participants that played the game improved to a greater degree than did control participants.

Table 4

Mean (standard deviation) accuracy on the word reading test (out of 8)

	Control			Massed			Distributed		
	Pre	Post	D	Pre	Post	D	Pre	Post	D
Simple	5.06 (1.74)	6.35 (1.66)	1.29	5.58 (1.46)	6.16 (1.49)	0.58	5.51 (1.63)	6.17 (1.52)	0.66
CV	3.89 (1.96)	4.96 (2.04)	1.07	4.18 (2.08)	5.48 (1.71)	1.31	4.09 (1.94)	4.99 (1.99)	0.90
Learned	3.14 (1.53)	4.18 (2.01)	1.04	3.42 (1.49)	4.85 (1.52)	1.44	3.46 (1.59)	5.26 (1.15)	1.80
Near	2.11 (1.64)	2.85 (1.74)	0.74	2.23 (1.61)	3.15 (1.84)	0.92	2.43 (1.88)	3.49 (1.86)	1.06
Medium	3.08 (2.46)	4.07 (2.13)	0.99	3.85 (2.18)	4.10 (2.50)	0.24	3.70 (2.23)	4.63 (1.79)	0.93
Far	2.93 (2.00)	3.17 (1.86)	0.24	2.81 (1.77)	3.65 (1.86)	0.84	3.17 (1.83)	3.93 (1.83)	0.76

Note. D = Difference between the pre-test and post-test scores. Note that participants that played the game improved to a greater degree than did control participants on words containing complex akshara.

Table 5

Mean (standard deviation) accuracy on the spelling test (out of 5)

	Control			Massed			Distributed		
	Pre	Post	D	Pre	Post	D	Pre	Post	D
Simple	3.25 (1.34)	4.19 (0.98)	0.94	3.59 (1.48)	4.03 (1.36)	0.44	3.34 (1.37)	4.11 (0.83)	0.77
CV	1.13 (1.54)	1.94 (1.40)	0.82	1.34 (1.46)	2.14 (1.52)	0.80	1.36 (1.44)	2.24 (1.26)	0.89
Learned	0.63 (0.81)	0.94 (0.99)	0.32	0.61 (0.92)	1.11 (1.01)	0.50	0.77 (0.92)	1.60 (1.37)	0.83
Near	0.50 (0.73)	0.57 (0.90)	0.07	0.44 (0.82)	0.70 (0.85)	0.27	0.36 (0.71)	0.71 (1.09)	0.36
Medium	0.33 (0.76)	0.65 (1.02)	0.32	0.33 (0.69)	1.03 (1.26)	0.70	0.37 (0.81)	0.81 (1.14)	0.44
Far	0.06 (0.20)	0.11 (0.34)	0.06	0 (0)	0.17 (0.49)	0.17	0 (0)	0.20 (0.62)	0.20

Note. D = Difference between the pre-test and post-test scores. Note that participants that played the game improved to a greater degree than did control participants on words containing complex akshara.

Table 6

Mean (standard deviation) accuracy on the akshara construction test (out of 7)

	Pre	Post
Control	4.89 (2.03)	6.09 (1.22)
Massed	4.97 (1.73)	6.06 (1.16)
Distributed	5.06 (1.82)	6.09 (1.26)

Note. There were six items but it was worth seven points because the last item /gle/ was worth two points: one point for the consonant /g/ and one point for the vowel diacritic /e/. There were no statistically significant differences across the three experimental groups.

Table 7

Mean (standard deviation) accuracy on the vocabulary test (out of 24)

	Control		Massed		Distributed	
	Pre	Post	Pre	Post	Pre	Post
Unrelated to game	15.06 (5.66)	16.61 (5.93)	14.00 (5.83)	15.34 (5.71)	14.40 (6.36)	16.57 (5.39)
Morphologically related to words in game	7.78 (5.00)	9.61 (5.84)	7.75 (5.41)	8.75 (6.54)	8.83 (6.06)	9.54 (6.38)
Learned in game	6.36 (4.98)	7.47 (4.63)	5.03 (4.59)	6.50 (5.56)	6.03 (5.81)	7.66 (6.01)

Note. There were no statistically significant differences across the three experimental groups.

Table 8

Average (standard deviation) raw scores on the math assessment

	Pre	Post
Control	40.78 (10.09)	54.39 (9.98)
Massed	42.91 (10.76)	56.8 (10.21)
Distributed	42.15 (14.26)	55.38 (18.11)

Note. Scores of 41 and 57 correspond to age equivalents of 8 years 6 months and 9 years 10 months, respectively (normed to a US population). The participants' average age was 9.26 years, so they were performing appropriately for their age group. Note that participants in all three groups showed equivalent levels of improvement.