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Spelling Challenges in Hindi

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Accepted for Publication in Psychological Studies, Sept. 2021

3  
4 Abstract

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6 Fourth standard students (8-10 years old) learning Hindi as an additional language played a  
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8 mobile game that teaches children to identify complex akshara (akshara that contain at least two  
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10 consonant components) and spell words that contain complex akshara. We analyzed the game  
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12 data to identify aspects of both akshara and words that are challenging to students. We replicated  
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14 some findings from previous studies: 1) students struggle with complex akshara that look  
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16 different than their components (i.e., opaque complex akshara); 2) they struggle with akshara  
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18 that have a non-linear arrangement of components; and 3) they struggle to spell words when  
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20 there is a mismatch between the orthographic and phonological syllable. Because we had more  
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22 stimuli than previous studies, we were able to examine finer comparisons in opacity and  
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24 linearity. Furthermore, we were the first to identify that students make rampant phonological  
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26 errors specifically on aspirated consonants, which are relatively rare in Hindi.  
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*Keywords: alphasyllabaries; Hindi; decoding; spelling; educational games*

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4 Spelling Challenges in Hindi5  
6 **1. Introduction**

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8 Identifying the difficult aspects of language learning is necessary to developing  
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10 curricula that address those challenges. For example, children struggle to learn homophones in  
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12 English (e.g., waste, waist), so teachers dedicate a great deal of time to homophones. Other  
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14 difficulties confront learners of other languages. Hindi poses unique challenges to learners both  
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16 because of complexities in its alphasyllabic orthography and because the spoken language  
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18 includes some challenging phonological contrasts. Hindi speakers worldwide number 380  
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20 million as of 2016: 260 million native speakers and 120 million second language speakers  
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22 (Lewis, Simons, & Fennig, 2016). Thus, research on learning Hindi has the potential to benefit  
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24 many learners. Furthermore, more research on alphasyllabic writing systems can shed light on  
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26 the cognitive mechanisms underlying reading and spelling that are generalizable to all the  
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28 world's languages.  
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35 **1.1 Orthographic Challenges**

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37 In Hindi's alphasyllabic orthography, phonemes combine in a non-linear manner to  
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39 form open syllabic graphs called *akshara*. Because there are more syllables than phonemes in  
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41 language, alphasyllabic writing systems have large graph (symbol) sets (Nag, 2011) that result  
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43 in high graphic complexity (Chang, Chen, & Perfetti, 2018).  
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48 There are three types of *akshara* based on number and composition of phonemes.  
49  
50 *Simple* *akshara* represent either a vowel phoneme or a consonant phoneme plus an inherent  
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52 schwa vowel. *Consonant-vowel (CV)* *akshara* have a consonant component and a vowel  
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54 diacritic. *Complex akshara* contain two or more consonants and may also have a vowel diacritic  
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56 (see Table 1).  
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These three akshara types have varying levels of difficulty for beginning readers. Simple akshara can provide some challenges for novice learners; many simple akshara are orthographically similar and thus easily confusable (e.g., म /m/ and भ /b<sup>h</sup>/) (Gupta, 2008). CV akshara are further challenging because the vowel diacritics are arranged in a non-linear manner around the consonant. Complex akshara are particularly difficult to learn, a result demonstrated in many alphasyllabaries (Telugu: Vasanta, 2004, Bengali: Nag and Sircar, 2008, Malayalam: Tiwari, Nair, and Krishnan, 2011, Kannada: Nag, 2007; Nag, Treiman, and Snowling, 2010; and Joshi, 2013). One reason is that the rules for concatenating consonants are complex and can result in opaque complex akshara. 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., स + त = स्त ; ण + ट = ण्ट; i.e., horizontally transparent). However, there are other ways of joining consonants (e.g., ट + ट = ट्ट ; द + व = द्द; i.e., other transparent). 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, when र /r/ is the first consonant in a complex akshara, it is represented by a curved line over the second consonant (e.g., र + द = र्द ; र + त = र्त). When र /r/ is the second consonant, it is depicted as either one or two diagonal lines (प + र = प्र ; क + र = क्र ; ट + र = ट्र ; ड + र = ड्र; i.e., R opaque). Finally, some complex akshara are very opaque and need to be memorized (e.g., क + ष = क्ष ; त + त = त्त ; त + र = त्र; द + द = द्द; i.e., memorize opaque). Nag (Nag, 2011; Nag et al., 2010) has demonstrated that students have more trouble spelling words with opaque complex akshara than with transparent complex akshara. One shortcoming of the previous research is that it clubs four categories of akshara (horizontally transparent, other transparent, R opaque, and memorize opaque) into just two broader categories: transparent and opaque. This study had a large enough sample size to

examine differences between all four categories, and thus allows us to get a more nuanced view of the effect of transparency on orthographic acquisition.

In addition to categorizing akshara by opacity, they can also be classified by linearity. *In-line akshara* are akshara whose components were ordered from left to right (e.g., स + क + आ = सका and क्ष + आ = क्षा). *Off-line akshara* are akshara which have adjacent components connected, but they are not ordered from left to right. For example, र + क = र्क, ट + ट + आ = ट्टा, and ल + ग + उ = लुग are considered off-line because in them two consecutive phonemes are joined, but vertically rather than horizontally. *Mis-sequenced akshara* are akshara with connections between non-adjacent components (e.g., स /s/+ क /k/+ इ /i/= स्कि /ski/). Children are more likely to misread words containing mis-sequenced complex akshara (Vaid & Gupta, 2002, experiment 2). Although Vaid and Gupta found that mis-sequenced akshara presented particular difficulties, they did not examine differences between in-line and off-line akshara. The present study has the sample size necessary to examine differences among all three categories of linearity.

## 1.2 Phonological Challenges

In addition to orthographic challenges, Hindi presents some phonological challenges. First, it contains many similar phonemes that contrast only in place of articulation or aspiration (e.g., द /d̪/ and ढ /d̪ʱ/ vary by place of articulation; क /k/ and ख /kʰ/ vary by aspiration). Further, some vowels contrast only in length (e.g., इ /i/ and ई /i:/ as well as उ /u/ and ऊ /u:/).

Children often struggle with these phonological distinctions. For example, Nag (2011) analyzed students' spellings and noted confusions between consonants that vary in only one feature, such as voicing (e.g., /g-k/), aspiration (e.g., /d̪-d̪ʱ/), and place of articulation (e.g., /l-ʎ/). (Also see Nag et al., 2010). Students also confuse vowel length frequently (Nag, 2011; Nag et al., 2010). For example, Nag (2011) found that a child wrote पुलीस instead of पुलिस (/poli:s/ instead of /polis/, police) as well as पुजा instead of पूजा (/pu:dʒa/ instead of /pu:dʒa/, prayer).

A second phonological challenge comes in its mapping to graphic units; the relationship between graphs and phonological units is not straightforward. Complex akshara can represent either consonantal blends or two adjacent consonants that cross a syllabic boundary. For example, in the word व्यायाम /wja.yam/ (exercise), the complex akshara व्या /wja/ represents a consonantal blend. In contrast, in the word बर्तन /bər.t̪ən/ (pan; kitchen utensil), the complex akshara र्त /r.t̪ə/ represents two consonants that cross a syllabic boundary. Nag (2014) found that children have more trouble decoding words in which the complex akshara straddles a syllabic boundary than when there is a match between the orthographic and phonological syllable.

One confound in Nag's research was that all of the blends were word initial whereas akshara that straddled syllabic boundaries were word medial, thus making it difficult to separate phonological effects from word position effects. This study seeks to disentangle the effects of word position and the phonology-orthography mapping.

### 1.3 Present Study

We developed a mobile game that taught children to decode and spell single Hindi words, with an explicit focus on complex akshara, which have been shown to be particularly difficult for children. We tested this game on 4th standard students living in Bangalore, India. This research had two goals: 1) determine whether the mobile game can successfully improve Hindi spelling and decoding skills and 2) shed light on common difficulties that children have in acquiring Hindi. The results of the first goal are described in Author (XXXX); the results of the latter goal will be described presently.

The study included three participant groups: two played two different versions of the game and one was an unseen control group. The assignment minimized differences in pre-test scores across the three groups. We used a pre-test, post-test design to measure the efficacy of the study and those results are described in Author (XXXX). Furthermore, for the two groups who

played the game, we analyzed the game results to shed light on the process of orthographic acquisition in Hindi. Those results are presented in the present paper.

This research is unique because the data are collected using a mobile game, rather than the paper-and-pencil methods used in previous research. Because game problems can be answered more quickly than paper-and-pencil problems, and children remain engaged in the game for long periods of time, we can easily collect large amounts of data. Thus, we have data from 70 students answering questions regarding 270 complex akshara and 250 words that contain one complex akshara. This contrasts with previous research that was based on groups numbering from 10 to 62 students who answered questions about stimulus sets ranging in size from 18 to 30 words (Nag, 2014; Nag et al., 2010; Vaid & Gupta, 2002). With this increased power, we can use finer grained categories of transparency and linearity than previous studies were able to.

#### 1.4 Challenges in Learning to Read an Alphasyllabary

Based on the research reviewed in the previous three sections, we predict that children will have more trouble with words that contain one of the vowels that vary in length (/i-i:/ and /u-u:/), because differences in vowel length can be difficult to discriminate. In fact, in the word final position, long and short vowel lengths are pronounced identically, except in careful, educated speech (Kachru, 2006). Confusions in vowel length have been observed in multiple Indian languages, including Hindi (Nag, 2011; Nag et al., 2010).

We also expect children to struggle with words that contain retroflex or aspirated consonants because Hindi dental/alveolar forms are more frequent than retroflex forms and unaspirated forms are more frequent than aspirated forms (Khan, Gupta, Rizvi, & Gupta, 1991). Analysis of the post-test data from these same participants suggests that they tended to have trouble with retroflex and aspirated forms (Author, XXXX). Confusions between aspirated-

unaspirated and dental-retroflex pairs have been seen in multiple Indian languages, including Hindi (Mathur & Nag, 2018; Nag, 2011; Nag et al., 2010). In the present study, we also expect children to struggle with opaque complex akshara, non-linear complex akshara, and complex akshara that straddle a syllabic boundary.

## 2. Methods

### 2.1 Game Design

The game consisted of two types of problems. In the first type, 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 heard a word and had 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 ग्रा /gra/, children had to spell the word ग्राम /gram/ [village]). It was not possible to get a problem “wrong”; students had to keep trying until they correctly solved the problem to move on to the next problem. To pass a level, the child had to finish all 20 problems before time ran out and earn a sufficient number of points.

#### 2.1.1 Akshara decomposition.

A complex akshara was displayed and the child had to choose the simple akshara of which it was composed 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

pronounced 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.

### 2.1.2 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. The child could listen to the word as many times as 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.

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). In terms of phonological errors, we expected there to be many dental-retroflex, aspirated-unaspirated, and vowel length confusions. Therefore, we typically included the counterparts among the foils (e.g., if a word contained a dental consonant we typically included its retroflex counterpart in the foils; if a word contained a short /i/, we included the long /i:/ as a foil). We also typically included the consonants within the complex akshara as singleton akshara (e.g., if the word contains the complex akshara /pr/, both /p/ and /r/ were included as foils).

All the words were chosen to be age-appropriate for the children. There are two centralized curricula in India, the Central Board of Secondary Education (CBSE) and the Indian

Certificate of Secondary Education (ICSE). All words were chosen from either CBSE or ICSE 3<sup>rd</sup>-5<sup>th</sup> standard textbooks.

### 2.1.3 Game play.

At the top of the screen were two bars, one that counted down the 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 had 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 was displayed explaining this and then the level re-started. If the child successfully completed a level, a congratulatory message was shown and then the next level began. The top of the screen contained 30 stars. One star was colored in for every level successfully completed.

#### 2.1.3.1 Levels.

The first level consisted of very high frequency words that the children should be familiar with (e.g., माता /maṭā/ [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/, /ε/, /o/, /ɔ/, and nasal) was taught within one problem. In levels 4-28, every word 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 had been taught in a previous level. The words in levels 2-30 were of mixed frequency (e.g. of high frequency word: तुम्हें /t̪umhẽ/ [you]; e.g. of low frequency

word: सुपाच्च /supatʃtʃə/ [easily digestible]). The game kept a log of all activity that is analyzed in the present study.

### *2.1.3.2 Game versions.*

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

The purpose of the two versions was to identify how stimuli should be spaced to optimize learning. In one version of the game, problems 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, but better long-term retention (Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Underwood, 1961). This study 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).

In the present study, we analyze how error patterns differ across the two game versions.

## 2.2 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 (i.e., rules of game play) 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.

### 2.3 Participants

All participants were in the 4<sup>th</sup> standard at a large all-girls private school in Bangalore, Karnataka, India. Because the study was conducted at a 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. Children who spoke Hindi or a language that was similar to Hindi (e.g., Marathi, Urdu) at home were excluded.

In school, 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; more instructional time is dedicated to their first additional language. Their choices for their first additional language are Hindi and Kannada; all of the children in our sample had chosen Hindi. The children received 45 minutes of Hindi instruction five days a week since the first standard (5-6 years old). The pedagogical approach is common for the region and consists of recitation, copywriting, and reading prescribed books (Nag, 2017).

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. 36 played the massed version of the game, 36 played the distributed version, and 36 were in an unseen control group. The three groups were matched on pre-test scores of reading and spelling. Five children did not complete the study because they went on vacation during the study or elected to discontinue with the study. Two of those children dropped out of the study before game play began; three of those children played the beginning levels of the game. In this paper, only data from the 70 students who played the game is analyzed.

The study was approved by the [redacted for review] IRB and followed the ethical guidelines of [redacted for review].

#### **2.4 Schedule**

The intervention was conducted over four weeks. Children were seen in groups of nine and each group was seen for 12 sessions, each 25 minutes long. Each child played the game at her own pace. Of the children who completed the study, 28 children finished all 30 levels. The

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3 remaining 39 children finished a minimum of 14 levels. The three children who did not complete  
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6 the study finished between eight and twelve levels.  
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### 8 **3. Results**

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10 The game tracked every touch screen response that the participants made. These data  
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12 were used to quantify the difficulty of various items and extract general principles about akshara  
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14 learning. First the data were cleaned to remove instances in which participants quit in the middle  
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16 of the problem. (This could happen when the game quit and re-started the level because time  
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18 expired or when children quit the game because the allotted time for the session had ended).  
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20 Thus, the problems the participants had completed solving remained. The data were then further  
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22 filtered to include only the first time a subject successfully completed a given item.  
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#### 28 **3.1 Akshara Decomposition**

##### 29 **3.1.1 Regression analysis.**

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31 First, participants' performance on the "akshara decomposition" problems was  
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33 analyzed using the number of touch screen responses required to arrive at the correct answer.  
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35 Touch screen responses included selecting an akshara, de-selecting an akshara, and asking for a  
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37 hint. It is important to note that all participants completed the problems in the earlier levels,  
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39 whereas fewer participants completed the problems in the higher levels. In the highest levels,  
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41 the highest performing participants and participants in the massed group are over-represented<sup>1</sup>.  
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47 It is also important to note that this analysis cannot account for instances in which the students  
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49 asked the experimenters for help.  
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60 <sup>1</sup> As reported in Author (XXXX), students played the massed version faster, so more students in that group  
61 reached the higher levels of the game.  
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Because the dependent variable (number of touch screen responses required to arrive at the correct answer) was a non-zero count variable, and there was overdispersion in its distribution, we used a zero-truncated negative binomial mixed effects model to analyze the data<sup>2</sup>. Mixed effects models allowed us to tease apart the effect of each independent variable on the number of touch screen responses, i.e., allowed us to determine the effect of each independent variable while holding the other variables constant. The independent variables were level, the spacing in the game, the number of components in the akshara, the linearity of the akshara, and the transparency of the akshara.

Level referred to the level number in the game. We expected students to improve through the game, and thus a negative effect of level number. Only levels 4-30 were included in the analysis because earlier levels did not have complex akshara. The variable was re-scaled.

Spacing referred to whether participants were in the massed or the distributed condition. Contrast coding was used to compare the effect of spacing. Number of components referred to the number of components in the akshara (e.g., an akshara with two consonantal components and one vowel diacritic would have 3 components). The minimum number of touch screen responses required to get the correct answer is equal to the number of components, so we expected a positive relationship. The number of components ranged from 2-5 with a median of 3. The variable was centered around its mean.

Linearity was coded in three levels. *In-line akshara* were akshara whose components were ordered from left to right (e.g., स + क + आ = स्का and क्ष + आ = क्षा). *Off-line akshara* were akshara which had adjacent components connected, but they were not ordered from left to right (e.g., र + क = र्क, ट + ट + आ = डा, and ल + ग + उ = लु were considered off-line because in them two

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<sup>2</sup> All models were fit in R using the glmmTMB package.

consecutive phonemes are joined vertically, not horizontally). *Mis-sequenced akshara* were akshara with connections between non-adjacent components. One large source of mis-sequencing was the /i/ vowel, which is written to the left of the consonants but pronounced after the consonants (e.g., स/s/+ क/k/+ इ/i/= स्कि/ski/). All complex akshara containing the /i/ vowel were coded as mis-sequenced. The other large source of mis-sequencing was the /r/ consonant when it was pronounced first in a consonant cluster. For example, र/r/ + क/k/ + आ/a/ = कर्ा was considered mis-sequenced because, in it, two non-consecutive phonemes, /r/ and /a/, are physically connected. Orthogonal contrasts were used to assess the effects of linearity. The first contrast compared the in-line and off-line akshara to the mis-sequenced akshara. The second contrast compared the in-line and off-line akshara to each other.

Transparency was coded in four levels. *Horizontally transparent* akshara were akshara that were formed by horizontally fusing the two consonantal components (e.g., स + त = स्त), the most common way of joining consonants. *Other transparent* akshara were akshara for which all components were visible, but were not joined horizontally (e.g., ट + ट = ट्ट; द + ध = द्ध). *R opaque* akshara were akshara that were opaque because they contained the phoneme /r/ (र), which always changes shape in complex akshara in a consistent manner (e.g., प + र = प्र; ट + र = ट्र; र + त = र्त). *Memorize opaque* akshara were inconsistent complex akshara that needed to be memorized (e.g., क + ष = क्ष; त + त = त्त). Orthogonal contrasts were used to assess the effect of transparency. The first contrast compared the *horizontally transparent akshara* to the *other transparent* akshara. The second contrast compared the *R opaque* akshara to the *memorize opaque* akshara. The third contrast compared the two transparent categories to the two opaque categories to assess the effect of transparency.

Examples of akshara belonging to the different levels of transparency and linearity, as well as the number of akshara in each level, are displayed in Table 2. Note that the four

categories are not evenly represented because the words were chosen to be representative of words children are exposed to; linear mixed effects models are able to handle uneven categories.

Because this is an intervention study, it is possible that differences between the akshara types either emerged or shrunk as a result of the instruction. To examine this possibility, we also included interactions between level and both transparency and linearity.

All random effects that significantly improved model fit according to the log likelihood test and allowed for model convergence were included. Subjects were included as a random intercept and the effects of level number, number of components, transparency, and linearity were allowed to vary by subjects. There were two item-level random effects: the consonant cluster and the vowel diacritic. Both item-level random effects were included as random intercepts and the effect of level number was allowed to vary by both item-level random effects.

As a baseline (mean of all other variables), participants required an average of 5.23 touch screen responses to correctly answer an akshara problem. There was a main effect of level; for each one standard deviation increase in level the number of touchscreen responses increased by a factor of 0.78,  $z = -4.63$ ,  $p < .001$ . This result suggests that participants improved throughout the game. There was no significant effect of spacing, indicating that participants in the massed and distributed conditions did not differ from each other,  $z = 0.15$ ,  $p = .879$ .

As expected, participants required more touch screen responses if the akshara contained more components,  $z = 3.11$ ,  $p = .002$ . Specifically, the number of required touch screen responses increased by a factor of 1.20 for each additional component.

Participants were affected by transparency and all expected comparisons were either significant or marginal. Participants required 1.59 times as many touch screen responses if an akshara was *other transparent* than if it was *horizontally transparent* ( $z = 3.28$ ,  $p = .001$ ) and

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4 1.23 times as many touchscreen responses if it was *memorize opaque* than if it was opaque  
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6 because it contained a /r/ (i.e., *R opaque*) ( $z = 1.81, p = 0.070$ ). Finally, participants required  
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8 1.23 times as many touch screen responses if an akshara was opaque than if it was transparent,  
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10  $z = 2.29, p = .022$ .

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Participants were also strongly affected by linearity and all expected comparisons were significant. Off-line akshara required 1.18 times as many touch screen responses as did in-line akshara ( $z = 3.40, p = .001$ ) and mis-sequenced akshara required 1.79 times as many touch screen responses as did the in-line and off-line akshara ( $z = 12.00, p < .001$ ) (see Table 3).

Finally, there were two interactions involving transparency and linearity. First, there was a significant interaction between the horizontally transparent/other transparent contrast and level,  $z = -2.65, p = .008$ . Second, there was a marginal interaction between the mis-sequenced/in-line and off-line contrast and level,  $z = -1.77, p = 0.078$ . The negative z-values indicate that the difference between the akshara types shrunk as the intervention progressed, i.e., performance on the difficult other transparent and mis-sequenced akshara improved to a greater degree than performance on the relatively easier horizontally transparent, in-line, and off-line akshara.

We were also interested in which hints the students chose more often to determine which type of hint students found more useful. Across all trials, students chose the sound hint 6693 times and color hint 1387 times. Thus, it seems as though the students found phonological information more useful than the visual information, suggesting that the students knew how to visually decompose the complex akshara but were having trouble remembering the phonological mappings.

### 3.1.2 Error analysis.

The regression analyses allow us to identify aspects of akshara that make them difficult to read. However, they do not provide information about common mistakes that students made

while attempting to solve those difficult problems. To answer that question, we performed a qualitative error analysis. For the analysis, we focused on the 13 problems that, on average, required more than 10 touch screen responses to respond to correctly (the threshold of 10 was chosen because it was approximately equal to the mean of  $4.4 + 1 \text{ SD}$  of 6.1). We included every instance in which a participant solved those 13 problems correctly (not just the first time) to increase the amount of data. These 13 problems were particularly difficult and analyzing the mistakes made while attempting these problems can shed light on common akshara recognition difficulties. As expected from the regression analyses, many of these difficult akshara were either opaque or mis-sequenced (see Table 4).

The most common errors (right hand column in Table 4) were determined by noting the patterns in the first few touch screen responses on the trials in which participants took the most touch screen responses to get the correct answer. For example, for akshara 22.6, a mis-sequenced, R-opaque akshara, (षा = र + ष + आ), the 30 trials that required the most touch screen responses were examined. In 16 of those 30 trials, the first akshara chosen were ष आ र. In another 5 trials, the first akshara chosen were ष र आ. Therefore, for this problem, the primary error type was coded as out of order. Thus, this qualitative analysis tells us that mis-sequenced akshara were difficult because, although students knew what the components were, they did not know the order of the components. Similarly, the table suggests that memorize opaque akshara were difficult because students often did not know which simple akshara comprise an opaque akshara.

## 3.2 Spelling

### 3.2.1 Regression analysis.

A similar analysis strategy was used for the words, using the number of touch screen responses until the correct answer was identified as the dependent variable. A zero-truncated negative binomial mixed effects model was used to identify features that made words more

difficult (see Table 5). The independent variables were 1) level, 2) the spacing in the game, 3) the number of akshara, 4) whether the word contained a retroflex consonant (ʈ, ʈʰ, ɖ, ɖʱ, or ɳ), 5) whether the word contained an aspirated consonant (kʰ, gʱ, tʃʰ, dʒʱ, tʰ, dʱ, tʰ, dʱ, pʰ, or bʱ), 6) whether the word contained either an /i/ or /i:/, 7) whether the word contained either an /u/ or /u:/, 8) whether the complex akshara spanned a syllabic boundary, 9) the transparency of the complex akshara, and 10) the linearity of the complex akshara. We also examined whether there was an interaction between level (1), spacing (2), and main effects 4-10.

We predicted a negative effect of level (1), because we expected participants to improve throughout the game. Only levels 4-28 were analyzed because the first three levels did not contain complex akshara and, in levels 29-30, every word contained two complex akshara. The variable was re-scaled.

We predicted that participants in the distributed group would require more touch screen responses than participants in the massed group because participants in the massed group already knew which complex akshara would be in the word. Contrast coding was used to assess the effect of spacing.

Number of akshara (3) referred to the number of akshara in the word. The minimum number of touch screen responses required to get the correct answer is equal to the number of akshara, so we expected a positive relationship. The number of akshara ranged from 2-5, with a median of 2. The variable was centered around its mean.

We expected participants to require more touch screen responses on words containing retroflex or aspirated consonants (4-5) or the vowels /i/, /i:/, /u/, or /u:/ (6-7). The number of words containing retroflex consonants, aspirated consonants, either an /i/ or /i:/, and either an /u/ or /u:/ were 25, 57, 97, and 40, respectively. Contrast coding was used to test the effect of the presence of difficult consonants and vowels (4-7). There may be an interaction between the

presence of a difficult consonant/vowel and spacing because, if the difficult phoneme is in the complex akshara, participants in the massed group should know what the correct form is. Hence, participants in the distributed group should show a larger effect of the presence of a challenging phoneme.

We also examined whether the complex akshara spanned a syllabic boundary (8) because previous research has shown that children struggle more with complex akshara that cross syllabic boundaries (Nag, 2014). We coded three levels of this variable: the complex akshara is a blend (49 akshara were in this level), the complex akshara is ambisyllabic (50 akshara), and the complex akshara crosses a syllabic boundary (151 akshara). We used orthogonal contrasts to examine the effect of this variable; the first compared blends to the two other levels; the second compared ambisyllabic structures to consonant clusters that cross the syllabic boundary. We also examined the interaction between this variable and spacing because participants in the distributed group should be more affected by difficult complex akshara, given the greater forgetting of a complex akshara expected after a longer retention interval.

To determine whether the complex akshara crossed a syllabic boundary (see Figure 3), we first looked at the position of the consonant cluster in the word. When the consonant cluster was in the initial position, we coded it as a blend, because in the initial position a consonant cluster must represent a blend (e.g., स्वाद /swaḍ/). When the consonant cluster was in the word final position, we listened to the word to see if there was an inherent schwa pronounced after the consonant (e.g., जन्म /jenmə/). When there was an inherent schwa, the consonant cluster was considered to be medial. If there was no inherent schwa, the consonant cluster was considered to be word final. Word final consonant clusters are coda blends, and hence were coded as blends (e.g., अन्त /ənt̪/). We also ensured that the consonant clusters were legal Hindi

codas according to Kachru (2006)<sup>3</sup>. Words with medial consonant clusters were the most challenging to code. The candidate syllabifications for VCCV structures are VC-CV, V-CCV, and VCC-V. Only the V-CCV syllabification matches the orthographic form. According to the *legality principle*, a V-CCV structure will only be chosen if the CC is a legal onset (Hooper, 1972; Pulgram, 1970 as cited in Ferrand, Segui, & Humphreys, 1997). So, we determined whether the consonant cluster is considered a legal onset by Kachru (2006). If it is not a legal onset, then the consonant cluster was considered to cross a syllabic boundary (e.g., गन्ना /gənn.na/). If the consonant cluster was a legal onset, then it was coded as ambisyllabic (e.g., मद्रस where both /məḍ.ras/ and /mə.ḍras/ are possible pronunciations).

Because the data are from an intervention study, it is possible that differences between the word types either emerged or shrunk as a result of the instruction. To examine this possibility, we also included interactions with level.

Variables 9-10 (transparency and linearity) were coded as they were in the akshara analyses. All random effects that significantly improved model fit according to the log likelihood test and allowed for model convergence were included. Subjects were included as a random intercept and the effects of level, number of akshara, and retroflexion were allowed to vary by subject. Word was included as a random intercept.

At baseline (all other variables at their mean), participants required 9.99 touch screen responses to answer a problem. Participants in the distributed version required 1.21 times as many touch screen responses per problem as did participants in the massed version,  $z = 2.85$ ,  $p = .004$ . This main effect of spacing was qualified by an interaction between spacing and level,

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<sup>3</sup> There were four words in which the final consonant cluster was not followed by a schwa but the consonant cluster was not listed as legal coda in Kachru (2006): सिक्ख, संघर्ष, सहर्ष, and हर्ष. However, because the native speaker who did our recordings pronounced the cluster as a blend, we coded it as a blend.

$z = 2.82, p = 0.005$ , which suggests that the difference between the two spacing conditions grew as the intervention progressed.

As expected, participants required more touch screen responses if the word contained more akshara,  $z = 13.58, p < .001$ . Specifically, they required 1.55 times as many touch screen responses for each additional akshara.

Participants struggled with words that contained aspirated consonants,  $z = 3.47, p = .001$ , but this main effect interacted with spacing,  $z = 2.38, p = .017$ . Post-hoc analyses<sup>4</sup> showed that although both the massed and distributed groups had trouble with words containing aspirated consonants, the effect was larger in the distributed group (massed:  $CE = 0.16, z = 2.86, p = 0.004$ ; distributed:  $CE = 0.22, z = 3.86, p < .001$ ).

There was also an interaction between syllabic boundary (crossing a syllabic boundary vs. ambisyllabic) and spacing,  $z = 3.48, p = .001$ . Post-hoc analyses showed that only the distributed group struggled with akshara that crossed syllabic boundaries (massed:  $CE = 0.02, z = 0.35, p = 0.726$ ; distributed:  $CE = 0.14, z = 2.11, p = .034$ ).

There was a three-way interaction among transparency (R-opaque compared to memorize opaque), spacing, and level,  $z = 3.01, p = 0.003$ . Post-hoc analyses showed that, in the massed group, there was no interaction between level and transparency (R-opaque compared to memorize opaque),  $CE = 0.05, z = 0.51, p = 0.607$ , but there was a marginal interaction in distributed group,  $CI = 0.20, z = 1.77, p = 0.076$ . This result suggests that, in the distributed group, the difference between R-opaque and memorize opaque shrunk as the game progressed.

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<sup>4</sup> Post-hoc analyses were conducted by running separate models for each group. The models were the same as the overall models but with the spacing variable removed. Note that for the distributed group we also had to remove two of the random slopes (number of akshara and retroflexion by subject) to achieve convergence.

There was a main effect of linearity; participants required significantly more touch screen responses when words contained mis-sequenced akshara,  $z = 2.02, p = 0.044$ . This main effect was qualified by a three-way interaction among linearity (in-line and off-line compared to mis-sequenced) spacing, and level,  $z = 2.16, p = 0.030$ . This interaction seems to stem from the fact that, although participants in both groups found words containing mis-sequenced akshara more difficult, in the massed group this effect shrank as the levels progressed,  $z = -0.17, p = 0.868$ , but in the distributed group this effect grew,  $z = 0.80, p = 0.596$ .

Finally, there was also a three-way interaction among linearity (in-line compared to off-line), spacing, and level,  $z = 2.10, p = 0.036$ . Again, although participants in both groups found words containing off-line akshara more difficult, in the massed group this effect shrank as the levels progressed,  $z = -0.56, p = 0.574$ , but in the distributed group this effect grew,  $z = 0.40, p = 0.688$ .

### 3.2.2 Error analysis.

As with the akshara, a qualitative analysis was conducted with the words to better understand error patterns. For the analysis, we focused on the 9 problems that, on average, required more than 21 touch screen responses to respond to correctly (the threshold of 21 was chosen because it was approximately equal to the mean of  $10.2 + 1 \text{ SD}$  of 11.3). We included every instance in which a participant solved those nine problems correctly (not just the first time) to increase the amount of data. These nine problems were particularly difficult and analyzing the mistakes made while attempting these problems can shed light on common spelling difficulties. As expected from the regression analyses, almost all of these difficult words (8 out of 9) contained complex akshara that straddled a syllabic boundary (see Table 6).

As seen in the table, there were also some examples of orthographic confusion. For example, in the word सुगन्ध, the orthographic foil न्ध was chosen fairly often. However, there

seemed to be more phonological difficulties than orthographic difficulties. For example, in the words बर्तन /bər.t̪ən/ and व्यायाम /wja.jam/, the orthographic foils are chosen very infrequently.

The regression analyses suggested that words containing aspirated consonants were particularly difficult because students often chose the unaspirated foil. For example, one of the words, सुगन्ध /su.gə̃n.d̪hə̃/, contained an aspirated consonant. The most commonly chosen foil was its unaspirated counterpart, न्द /nd̪/.

Many splitting errors were present in the data; गणतन्त्र /gə̃n.t̪n.t̪rə̃/ is a particularly good example of this. The complex akshara त्र is composed of three consonants, न /n/, त /t̪/, and र /r/. The त and र combine to form the opaque complex akshara त्र. Then, the न is added to form the complete form त्र. The most common split-type errors were choosing न and त्र. The third most common split-type error was choosing त्र. Thus, it seemed that the three consonant string was especially challenging and students tended to choose different combinations of the three consonants.

Interestingly, many mistakes involving vowel length were observed. For example, the word चिकित्सक /t̪i.ki.t̪sək/ has two short /i/ sounds. Students often chose the long /i:/ by mistake. Similar mistakes were seen in आनन्दित /a.nə̃n.d̪i.t̪/, परिवर्तित /pə̃.ri.wə̃r.t̪i.t̪ə̃/, निर्दयी /nir.d̪ə̃.ji:/, and सुगन्ध /su.gə̃n.d̪hə̃/. This result is interesting because the regression suggests that vowel length does not affect the number of touch-screen responses. This discrepancy between the error analysis and the regression could be caused by subject-specific variation; a few subjects could be driving this result in the error analysis, whereas subject-specific variation is accounted for in the regression.

Two words had particularly interesting response patterns. First, for the word बर्तन /bər.t̪ən/, students commonly chose the combination, ब /b/, र /r/, त /t̪ən/ (this combination was chosen in 48 out of 93 trials at some point and on 26 trials as the first three akshara). This is

interesting because this combination is phonologically correct; both बर्तन and बरतं would be pronounced as /bər.t̪ən/.

Second, for the word दद /d̪ər.d̪ə/, on 33 out of 108 trials द /rd̪/ was chosen first. This suggests that participants may have known that द has the phonemes /r/ and /d̪/, but were confused about their order. This order confusion mirrors some of the common mistakes students made on the akshara problems.

#### 4. Discussion

In this study, we developed a mobile game that teaches children complex Hindi akshara, i.e., akshara that contain at least two consonant components. There were two types of problems: akshara decomposition (decomposing an akshara into its components) and spelling (spelling words that contain complex akshara). There were two game versions that varied only in terms of the order of stimuli presentation: massed (in which the students decomposed an akshara and then immediately spelled a word that contained that akshara) and distributed (in which students decomposed 10 akshara and then spelled 10 words that contain them). Our goal was to identify features of akshara and words that affect learning.

We found that transparency and linearity strongly affected akshara recognition (see Table 2). Students found other transparent akshara more challenging than horizontally transparent akshara. Opaque akshara that needed to be memorized because they did not follow any standard concatenation rules (i.e., memorize opaque akshara) were more challenging than akshara that were opaque because they contained an /r/ (i.e., R opaque akshara), likely because the students simply did not know which simple akshara comprised the complex akshara. Furthermore, students found opaque akshara more challenging than transparent akshara. In terms of linearity, students found off-line akshara more difficult than in-line akshara, but mis-

sequenced akshara were the most difficult. Students seemed to know which simple akshara comprised the mis-sequenced akshara but placed them in the incorrect order.

The properties of complex akshara also differentially affected word recognition. Overall, participants struggled with words that contained mis-sequenced complex akshara. Furthermore, when the complex akshara was medial, participants in the distributed group struggled more when it crossed a syllabic boundary than when it was ambisyllabic. This effect was likely driven by a large number of errors in which students selected simple akshara foils that represent one of the consonantal components in the correct complex akshara (i.e., split-type errors). In addition to properties of the complex akshara, students also struggled when words contained aspirated consonants, likely because they selected their more frequent unaspirated counterparts.

In general, the distributed group was more affected by word properties than was the massed group, likely because they did not have the benefit of recent experience with the complex akshara. Specifically, they showed larger effects of the presence of aspirated consonants and mismatches between the orthographic and phonological syllable.

In the present study, we found that split-type errors are quite common. Additionally, the present study, which was conducted with second language learners, and the Nag et al. (2010) study, which was conducted with native speakers, both found that phonological errors were more common than orthographic errors. However, the proportion of phonological errors may have been particularly high in the present study because second language learners typically struggle with certain phonological contrasts, such as the aspiration contrast (Mathur & Nag, 2019). Furthermore, the proportion of phonological errors may have been particularly high in our sample because many participants were native speakers of Dravidian languages (i.e., South Indian languages such as Kannada and Tamil). Aspiration was not phonemic in Proto-Dravidian,

and most words with aspirated consonants in Dravidian languages are loan words from Indo-Aryan languages (Krishnamurti, 2003). Sridhar (1990) found that Kannada speakers tend to drop the aspiration contrast.

Our results largely replicate previous studies. However, because our study included more stimuli, we were able to expand upon and qualify those results. For example, Nag et al. (2010) noted many confusions between aspirated-unaspirated pairs. Our results suggest that students may be more likely to spell a word containing an aspirated consonant with its unaspirated counterpart than the other way around, likely because of the distributional properties of the language.

Furthermore, we replicated Nag et al.'s (2010) finding demonstrating that opaque akshara are more difficult than transparent akshara. That study had only two categories of words (words with transparent or opaque complex akshara) with five words in the former category and three words in the latter. Due to our large number of stimuli, we were able to have four categories of complex akshara (horizontally transparent, other transparent, R opaque, and memorize opaque). We demonstrated that there are significant differences across all four levels of transparency.

We were also able to replicate Nag's (2014) finding that complex akshara that cross a syllabic boundary are particularly difficult. Nag compared blends occurring in the word initial position to complex akshara that are in a medial position and cross a syllabic boundary. She found that the blends were easier than the complex akshara that crossed a syllabic boundary. However, word position was a confounding factor in that study. In our study, we had blends that occurred in both word initial and word final positions. We also had two types of medial complex akshara: ambisyllabic and those that definitively cross a syllabic boundary. We found that complex akshara that cross a syllabic boundary are more difficult than ambisyllabic complex

akshara. Thus, we demonstrated that a mismatch between the orthographic and phonological syllable hinders reading when word position is controlled for.

Finally, we replicated Vaid and Gupta's (2002) finding that non-linear complex akshara are particularly challenging. Their study found that children had trouble reading words that contained a medial complex akshara with an /i/ diacritic (e.g., मस्जिद /məsdʒid/ in which the /i/ is written before the /sdʒ/ but pronounced after). Children often mispronounced the words by placing the /i/ in between the two consonants (e.g., /məsidʒəḍ/). We extended these findings by having three categories of linearity: in-line, off-line, and mis-sequenced. The mis-sequenced category included /sdʒi/ type akshara, in addition to akshara that are mis-sequenced due to the /r/ diacritic. We found that off-line complex akshara are more difficult than in-line complex akshara, but mis-sequenced complex akshara are the most difficult. Similar to Vaid and Gupta, we found that mis-sequenced complex akshara are difficult because students do not know the order of the components.

We can consider our results from the perspective of the three aspects to alphasyllabary orthographic learning proposed by Nag (2017): global (whole akshara recognition), analytic (attending to akshara components), and strategic (understanding how akshara function in word contexts) (Nag, 2017). Overall, our results suggest that the students in our 4<sup>th</sup> standard sample are in the analytic stage of akshara recognition and are having some trouble entering the strategic phase. If students were still in the global phase, we would expect students to be confused by orthographic foils, but orthographic foils were rarely selected. Furthermore, if students were attending to the whole akshara, they should not be confused by a non-linear arrangement of components within the akshara. The fact that students struggled with off-line and mis-sequenced complex akshara suggests that they are paying attention to akshara components, thus placing them in the analytic stage. Finally, the fact that students struggled with complex akshara that

cross a syllabic boundary suggest that they are having trouble understanding some of the more complex ways that akshara fit into word contexts, an important aspect of being strategic in the use of akshara to spell words.

Most studies that look at common challenges in learning to read and spell in an alphasyllabary have students either spell words using a pencil-and-paper approach or have students read words aloud. Although these methods are ecologically valid, it is challenging to collect data on many words using these methods given time constraints and children's limited attention spans. We collected data using a touchscreen mobile game, which allowed us to collect data on a large number of stimuli. Thus, we had enough power to look at finer categories (e.g., four categories of transparency as opposed to just two).

Although this data collection method allows us to increase our power, it does have the drawback that we can only identify errors that we included in our foils. For example, based on the prior literature, we expected students to confuse dental-retroflex consonants so we typically included place-of-articulation foils. However, if a student typically makes an error that we did not anticipate, we did not make a foil for it and hence would not be able to capture it in our data. Furthermore, all of our foils were legal akshara. If a student has trouble with akshara formation and often spells words with orthographically illegal akshara, we would not capture those errors in our data. Thus, studies that employ naming or paper-and-pencil techniques are better able to capture errors that cannot be anticipated by the prior literature.

To conclude, this study used a novel methodology for data collection, a touch screen game, which allowed us to collect data on many words. The study adds to our knowledge of common challenges students face in learning to read and write in an alphasyllabary. Our data identified three aspects of Hindi that are particularly difficult for students: 1) phonological features that are relatively infrequent (aspirated consonants); 2) difficult complex akshara (non-

linear and opaque complex akshara); and 3) words in which there is a mismatch between the orthographic and phonological syllable. In the future, we would like to collect similar data, but with native Hindi speakers, to identify the differences between native speakers and second language learners. We predict that native speakers will have less trouble with aspirated consonants, but we need to test that hypothesis. Furthermore, we want to determine whether there are additional differences between native speakers and second language learners. Finally, the present study only included spelling, not reading. Although other reading studies have been conducted in the past, not with the large number of words in the current study. We would like to add a reading measure to determine whether akshara and word properties have the same effects on reading as they do on spelling.

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Level → ★ ★ ★ ★ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆

शेष समय ← Time Remaining

अंक ← Points

ग्रा = ? + ? + ?

आ	ओ	अं	ग	ज	त
ध	प	य	र	ल	व

रंग  
Color  
ग्रा → ग्रा

आवाज़  
Sound

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 ग्रा /gra/ is shown. The simple akshara options are below. The three correct answers have red boxes around them. The two hint buttons, color and sound, are at the bottom. This figure was previously published in Author (XXXX).

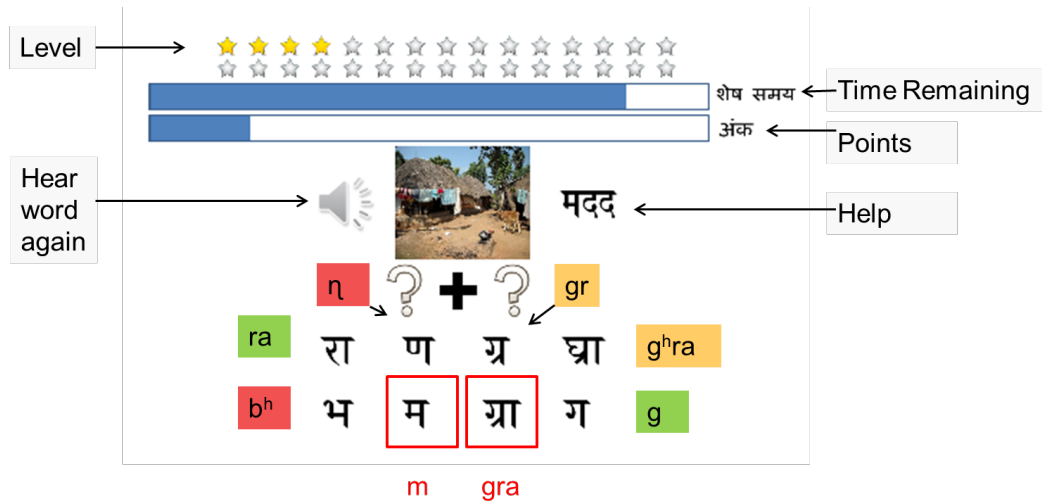


Figure 2: A screenshot of a spelling problem. Children would hear the word /gram/ (village). They could press the speaker to hear it again. The picture depicts the meaning of the word. All pictures were chosen to be age and culturally appropriate (e.g., modest dress, no alcohol, images depicted both 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). Note that the complex akshara they just learned (/gra/) is in this word. 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. This figure was previously published in Author (XXXX).

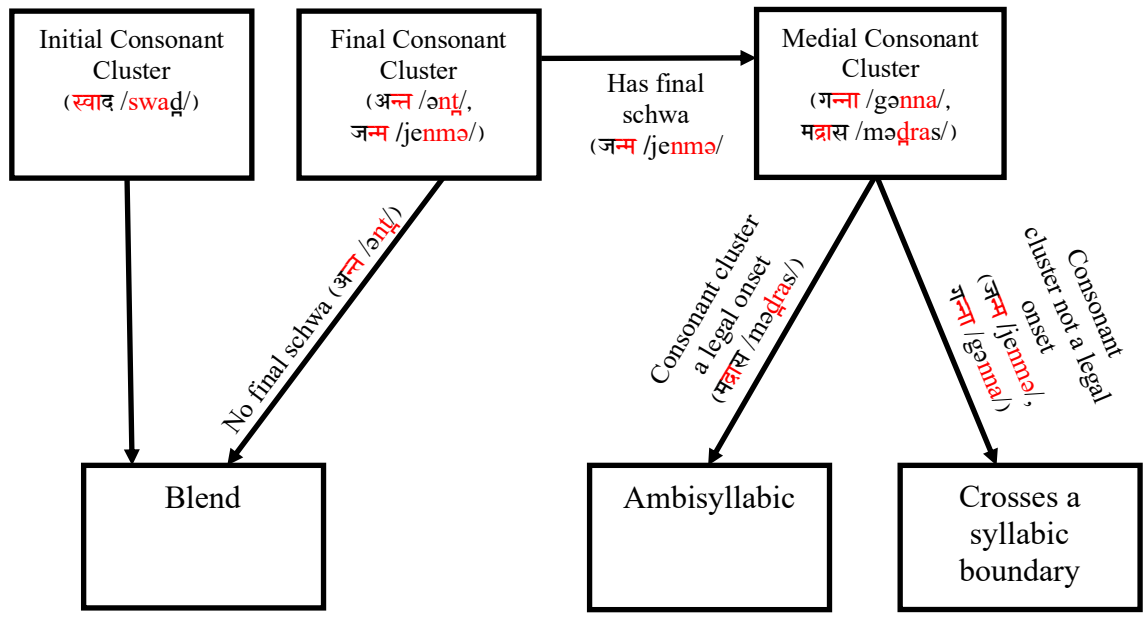


Figure 3: A decision tree showing how we classified the syllabic structure of the complex akshara.

Table 1

*Examples of different akshara types*

Akshara Type	Akshara	Phonology
Simple Vowel	उ	/u/
Simple Consonant	स	/sə/
CV	सु	/su/
Complex	स्तु	/st̪u/

Table 2

*Examples of akshara at all levels of linearity and transparency*

Variable	Levels	Description	Examples	Number of akshara in the game
Linearity	In-line	Components ordered from left to right	स + क + आ = स्का क्ष + आ = क्षा	162
	Off-line	Adjacent components were connected, but they were not ordered from left to right	र + क = र्क ट + ट + आ = ट्टा ल + ग + उ = ल्यु	84
	Mis-sequenced	Connected non-adjacent components	स + क + इ = स्कि र + क + आ = र्का	24
Transparency	Horizontally transparent	Formed by horizontally fusing two consonantal components	स + त = स्त	161
	Other transparent	All components visible, but not joined horizontally	ट + ट = ट्ट द + ध = द्ध	9
	R opaque	Opaque because they contained the phoneme /r/ (र)	प + र = प्र ट + र = ट्र र + त = र्त	69
	Memorize opaque	Inconsistent and needed to be memorized	क + ष = क्ष त + त = त्त	31

Table 3

*Fixed effect estimates (top) and variance estimates (bottom) for zero-truncated negative binomial mixed effects model with akshara-level data.*

<b>Fixed Effect</b>	<b>CE</b>	<b>SE</b>	<b>z</b>	<b>p</b>
Intercept	1.65	0.07	23.58	<.001*
Level	-0.25	0.05	-4.63	<.001*
Spacing	0.004	0.02	0.15	.879
Number of components	0.18	0.06	3.11	.002*
In-line vs. off-line	0.17	0.05	3.40	.001*
In-line and off-line vs. mis-sequenced	0.58	0.05	12.00	<.001*
Horizontal transparent vs. Other transparent	0.47	0.14	3.28	.001*
R opaque vs. Memorize opaque	0.21	0.11	1.81	.070†
Transparent vs. Opaque	0.20	0.09	2.289	.022*
In-line vs. off-line*Level	0.02	0.04	0.38	.706
In-line and off-line vs. mis-sequenced*Level	-0.07	0.04	-1.77	.078†
Horizontal transparent vs. Other transparent*Level	-0.34	0.13	-2.65	.008*
R opaque vs. Memorize opaque*Level	-0.15	0.09	-1.64	.100
Transparent vs. Opaque*Level	-0.05	0.07	-0.63	.531
<b>Random Effect</b>	<b>s<sup>2</sup></b>			
Level   Consonant cluster	0.02			
Consonant cluster	0.04			
Level   Vowel	0.01			
Vowel	0.01			
Level   Subject	<0.01			
Number of components   Subject	<0.01			
Linearity: in-line   Subject	<0.01			
Linearity: off-line   Subject	0.01			
Linearity: mis-sequenced   Subject	0.06			
Transparency: horizontally transparent   Subject	<0.01			
Transparency: other transparent   Subject	0.04			
Transparency: r opaque   Subject	0.04			
Transparency: memorize opaque   Subject	0.06			
Subject	<0.001			

*Note.* Number of observations: 25139. CE is an abbreviation for Coefficient Estimate, i.e., the estimated regression coefficient. \* $p \leq .05$  † $p \leq .10$ .

Table 4

*Difficult akshara problems.*

Level. Problem	Complex akshara	Phonology	Components	Why was this akshara difficult?	What common errors did students make?
4.7	त्त	t̪t̪	त त	Memorize opaque akshara	Participants knew one akshara was त; randomly guessed the second akshara
5.7	र्ता	r̪t̪a	र त आ	R opaque akshara Mis-sequenced akshara Orthographic similarity	-Out of order -This akshara looks similar to the CV akshara तो (त + ओ); many participants chose the vowel ओ
6.9	स्त्र	s̪t̪r	स त र	Memorize opaque akshara	Many participants chose स and र but missed त
7.2	क्षी	k̪ʃi:	क ष ई	Memorize opaque akshara	Some participants chose क and ई; others chose ष and ई
7.4	न्ति	n̪t̪i	न त इ	Mis-sequenced akshara	Out of order
7.9	स्त्रि	s̪t̪ri	स त र इ	Memorize opaque akshara Mis-sequenced akshara	Out of order
9.2	ण्टि	ɳ̪t̪i	ण ट इ	Mis-sequenced akshara	Out of order
9.3	र्णि	r̪ɳ̪i	र ण इ	R opaque akshara Mis-sequenced akshara	Out of order
9.6	ष्ट्री	ʃ̪t̪ri:	ष ट र ई	R opaque akshara Off-line akshara	Out of order
14.3	र्ती	r̪t̪i:	र त ई	R opaque akshara Mis-sequenced akshara	Out of order
19.7	द्दी	d̪d̪i:	द द ई	Memorize opaque akshara	Participants did not seem to know that द + द = द्द; they used the hint sound and chose consonants that were phonologically similar
22.1	क्षि	k̪ʃi	क ष इ	Memorize opaque akshara Mis-sequenced akshara	Both श and ष make the /ʃ/ sound. Many participants chose श by mistake. <sup>1</sup>
22.6	र्षा	r̪ʃ̪a	र ष आ	R opaque akshara Mis-sequenced akshara	Out of order

*Note.* The 4<sup>th</sup> column shows the simple akshara that comprise the complex akshara. The color-coding scheme is: green = vowel; red = र/r/, this akshara always changes shape when part of a complex akshara; purple = memorize opaque akshara, black/blue = consonant akshara that is easily visible in the complex akshara. In the last column, out of order means that the students selected the correct components, but in the wrong order.

<sup>1</sup> Although traditionally श and ष are pronounced as /ʃ/ and /ʃ̪/ respectively, the difference is diminishing in modern Hindi (Kachru, 2006).

Table 5

*Fixed effect estimates (top) and variance estimates (bottom) for zero-truncated negative binomial mixed effects model with word-level data.*

<b>Fixed Effect</b>	<b>CE</b>	<b>SE</b>	<b>z</b>	<b>p</b>
Intercept	2.30	0.08	29.91	<.001*
Level	-0.10	0.06	-1.61	.106
Spacing	0.19	0.07	2.85	.004*
Number of akshara	0.44	0.03	13.58	<.001*
Retroflexion	0.15	0.08	1.80	.072†
Aspiration	0.19	0.06	3.47	.001*
Syllabic structure (Blend vs. ambisyllabic and crosses syllabic boundary)	-0.07	0.06	-1.05	.293
Syllabic structure (Ambisyllabic vs. crosses syllabic boundary)	0.08	0.06	1.24	.215
i	0.03	0.05	0.60	.547
u	0.10	0.06	1.61	.108
In-line vs. off-line	0.04	0.08	0.45	.654
In-line and off-line vs. mis-sequenced	0.19	0.10	2.02	.044*
Horizontal transparent vs. Other transparent	0.01	0.22	0.04	.968
R opaque vs. Memorize opaque	-0.06	0.11	-0.58	.562
Transparent vs. Opaque	-0.05	0.11	-0.42	.672
Retroflexion x Spacing	0.06	0.05	1.31	.190
Retroflexion x Level	0.14	0.07	1.95	.051†
Spacing x Level	0.11	0.04	2.82	.005*
Aspiration x Spacing	0.07	0.03	2.38	.017*
Aspiration x Level	-0.01	0.06	-0.14	.89
Syllabic structure (Blend and ambisyllabic vs. crosses syllabic boundary) x Spacing	0	0.04	-0.07	.945
Syllabic structure (Ambisyllabic vs. crosses syllabic boundary) x Spacing	0.12	0.03	3.48	.001*
Syllabic structure (Blend and ambisyllabic vs. crosses syllabic boundary) x Level	-0.06	0.05	-1.14	.254
Syllabic structure (Ambisyllabic vs. crosses syllabic boundary) x Level	-0.09	0.06	-1.43	.153
i x Spacing	-0.01	0.03	-0.24	.814
i x Level	-0.02	0.05	-0.45	.657
u x Spacing	0.05	0.03	1.41	.159
u x Level	-0.08	0.07	-1.21	.225
Transparency (Transparent vs. Opaque) x Spacing	-0.06	0.06	-1.11	.266
Transparency (R opaque vs. Memorize opaque) x Spacing	0	0.06	0.08	.939
Transparency (Horizontal transparent vs. Other transparent) x Spacing	0.19	0.11	1.65	.099†
Transparency (Transparent vs. Opaque) x Level	0.08	0.1	0.74	.461
Transparency (R opaque vs. Memorize opaque) x Level	0.12	0.1	1.17	.241

Transparency (Horizontal transparent vs. Other transparent) x Level	-0.2	0.19	-1.02	.31
Linearity (In-line and off-line vs. mis-sequenced) x Spacing	0.01	0.04	0.29	.771
Linearity (In-line vs. off-line) x Spacing	-0.01	0.05	-0.17	.862
Linearity (In-line and off-line vs. mis-sequenced) x Level	0.02	0.08	0.32	.751
Linearity (In-line vs. off-line) x Level	0	0.08	-0.05	.963
Retroflexion x Spacing x Level	0.02	0.04	0.43	.667
Aspiration x Spacing x Level	0.06	0.03	1.81	.070†
Syllabic structure (Blend and ambisyllabic vs. crosses syllabic boundary) x Spacing x Level	-0.03	0.03	-0.88	.380
Syllabic structure (Ambisyllabic vs. crosses syllabic boundary) x Spacing x Level	-0.06	0.04	-1.56	.120
i x Spacing x Level	-0.02	0.03	-0.65	.518
u x Spacing x Level	0.03	0.04	0.88	.381
Transparency (Transparent vs. Opaque) x Spacing x Level	-0.07	0.06	-1.11	.269
Transparency (R opaque vs. Memorize opaque) x Spacing x Level	0.2	0.07	3.01	.003*
Transparency (Horizontal transparent vs. Other transparent) x Spacing x Level	0.09	0.12	0.79	.431
Linearity (In-line and off-line vs. mis-sequenced) x Spacing x Level	0.09	0.04	2.16	.030*
Linearity (In-line vs. off-line) x Spacing x Level	0.11	0.05	2.10	.036*
<b>Random Effect</b>	<b>s<sup>2</sup></b>			
Word	0.10			
Subject	0.05			
Level   Subject	<0.01			
Number of akshara   Subject	0.01			
Retroflexion   Subject	0.01			

*Note.* Number of observations: 21464. CE is an abbreviation for Coefficient Estimate, i.e., the estimated regression coefficient. \* $p \leq .05$ . † $p \leq .10$ .

## Table 6

### *Difficult word problems.*

[Table on next page; too large to fit table and caption on same page]

*Note.* The first row has the level number, problem number, difficult word, its pronunciation, and its meaning. The next row shows the options the students could choose from. The correct responses are on the left and the foils are on the right. The correct responses are listed in the order they appear in the word. The foils are listed from most to least selected. The next row shows the pronunciations of the akshara. The complex akshara in the word is bolded. The next row shows the foil type. P = phonological, S = splitting the complex akshara, O = orthographic, C = combining two akshara. For example, in the word बर्तन /bər.t̪ən/, the foil भ /b<sup>h</sup>/ is phonologically similar to ब /b/. Therefore, भ is marked as 'P' and both akshara are coded blue to show their connection. व is orthographically similar to ब. Therefore, व is marked as 'O' and both akshara are coded blue. The complex akshara is र्त्न /r̪t̪n/. The foils र /r/ and त /t̪/ are examples of incorrectly splitting the complex akshara. Therefore, they are marked as 'S' and all three akshara are color-coded red. Finally, this word has the sounds /t̪/ and /n/ in different akshara. The र्त्न /r̪t̪n/ foil combines both of those sounds and is therefore marked as 'C'. It is not color coded because it is not associated with one particular akshara. Finally, the number of touch screen responses is listed in the last row. Note that for correct akshara, schwas are shown as appropriate. For the foils, no schwas are shown because schwa placement depends on the word context.

6.6 चिकित्सक / tʃi.ki.t.sək/ (doctor)											
Akshara	चि	कि	त्स	क		की	ची	स	त	ख	
Phonology	tʃi	ki	t.sə	k		ki:	tʃi:	s	t	k <sup>h</sup>	
Foil Type						P	P	S	S	P	
# responses	243	262	312	273		136	135	133	115	95	
6.7 बर्तन /bər.tən/ (pan; kitchen utensil)											
Akshara	ब	र्त	न			र	त	भ	ट	त	व
Phonology	bə	r.tə	n			r	tən	b <sup>h</sup>	ɾt	t	w
Foil Type						S	C	P	P	S	O
# responses	224	372	180			168	155	93	42	37	20
8.2 गणतन्त्र /gən.tən.tɾə/ (Republic)											
Akshara	ग	ण	त	न्त्र		न	त्र	न्त	घ	र	ट
Phonology	gə	ɳ	tə	n.tɾə		n	tɾ	nt	g <sup>h</sup>	r	t
Foil Type						S/P	S	S	P	S	P
# responses	197	165	199	300		142	130	128	83	42	24
9.8 दर्द /dər.də/ (pain)											
Akshara	द	र्द				ट	द्र	घ	ढ	ड	र
Phonology	də	r.də				ɾd <sup>h</sup>	dr	ɾd <sup>h</sup>	d <sup>h</sup>	d	r
Foil Type						P/O	C	P	P/O	P	S
# responses	250	737				253	170	148	132	86	62
13.6 सुगन्ध /su.gən.d̪hə/ (fragrance)											
Akshara	सु	ग	न्ध			न्द	घ	स्	न्ध	घ	न
Phonology	su	gə	n.d̪hə			nd	g <sup>h</sup>	su:	ng <sup>h</sup>	d̪h	n
Foil Type						P	P	P/O	O	S	S
# responses	134	177	173			153	109	93	92	67	24
14.5 निर्दयी /nir.də.ji:/ (merciless)											
Akshara	नि	र्द	यी			र	यि	नी	ई	णि	द
Phonology	ni	r.də	ji:			r	ji	ni:	ɾd	ɳi	d
Foil Type						S	P	P	P	P	S
# responses	176	265	165			103	97	85	65	46	42
15.5 परिवर्तित /pə.ri.wər.t̪i.t̪ə/ (change)											
Akshara	प	रि	व	र्ति	त	र्ती	री	र	ति	फ	
Phonology	pə	ri	wə	r.t̪i	t̪ə	ɾti:	ri:	r	t̪i	p <sup>h</sup>	
Foil Type						P	P	S	S	P	
# responses	170	177	216	331	210	140	109	102	74	14	
19.1 आनन्दित /a.nən.d̪i.t̪/ (rejoice)											
Akshara	आ	न	न्दि	त		न्दी	अ	थ	दि	ण्दि	
Phonology	a	nə	n.d̪i	t̪		ndi:	ə	t̪ <sup>h</sup>	d̪i	ɳd̪i	
Foil Type						P	P	P	S	P	
# responses	182	226	280	261		145	115	105	76	72	
23.1 व्यायाम /wja.jam/ (exercise)											
Akshara	व्या	या	म			य	या	व	व्य	भ	ब्या
Phonology	wja	ja	m			j	jam	w	wj	b <sup>h</sup>	bja
Foil Type						P	C	S	P	O	O
# responses	166	216	100			81	76	60	43	17	14